This Appendix contains a working matrix of slides on maintenance, material, and management. These slides were used by Group I in tasking NASA to respond to requests for information or specific issues. Each matrix subject addresses an action/issue, background/facts, findings, recommendations and source documentation. By using this tool, Group I was able to engage NASA on potential final report inclusions.
Group 1

INVESTIGATION MATRIX
### Group 1 Investigation Matrix

<table>
<thead>
<tr>
<th>Category</th>
<th>E/T Foam</th>
<th>RCC</th>
<th>Tile</th>
<th>Orbiter</th>
<th>Other</th>
<th>Organization</th>
<th>Contract</th>
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Reset Matrix

Presenter: CAIB/Group 1 | Date: FINAL | Slide: 2 of 32
ET – Foam
Design – Certification

ET Bipod Ramp Redesign
Geometry of LH2-IT Flange
Super Lightweight Tank Design Change

1-1
1-2
1-3
COLUMBIA ACCIDENT INVESTIGATION BOARD

ET - Foam Design - Certification

- Action / Issue:
  - Redesign

- Background / Facts:
  - Bipod fitting enclosure redesign efforts are already underway
  - Effort was initiated after loss of bipod ramp foam on STS-112
  - Lessons learned indicate use of SLA is not necessary
  - Five designs proposed
    - All eliminate SLA
    - Two minimize size of sprayed-on foam ramp with metal (Ti) fitting
    - One uses a bare metal (Ti) fitting
    - Two use an Inconel housing to protect the metal fitting
  - Leading candidate (2a) is a bare metal fitting with no foam
  - Preliminary Design Review scheduled for 17-19 Jun 03
  - Critical Design Review planned for ~15 July 03

- Recommendations:
  - NASA efforts to redesign the bipod fitting enclosure must continue.
  - Efforts shall include testing and analyses that account for the complex combination of aerodynamic loads, structural loads, aerodynamic heating, cryogenic backfire temperatures, and changes in atmospheric pressure.
  - Tests and analyses must be sufficient to ensure that the loss of foam or hardware from this region will not happen in the future.
  - The redesign of the bipod fitting enclosure will be a Return-To-Flight requirement.
  - If foam is still required on bipod fitting:
    - Tighten acceptable temperature & humidity spray envelope
    - Standardize operator techniques
    - Consider use of robotics to fabricate bipod ramp
    - Develop and validate NDE techniques to check for defects

ET - Foam Design - Certification

Historical Bipod Ramp Changes - 1

Historical Bipod Ramp Changes - 2

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**ET - Foam Design - Certification**

- **Action / Issue**: Geometry of the LH2-IT flange could contribute to foam loss
- **Background / Facts**:
  - LH2-IT geometry provides several paths where LN2 can possibly get into the flange area
  - Solid N2 to GN2 state transitions could possibly contribute to foam loss
  - A "Y" joint is formed where the LH2-IT connection is made to provide a reservoir where LN2 can collect

- **Findings**:
  - Bolt holes, shim gaps and stringer venting could provide a path for LN2 to get behind the foam in the flange closeout area
  - During ascent, stresses in flange area change between tension and compression
  - LN2 path back to the IT could possibly be sealed leading to foam being "popped" off
  - Foam loss from the LH2-IT flange region has been observed on ~70% of missions where imagery was available

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**Recommendations**:
- NASA must understand the relationship between the complex LH2-IT flange geometry and the high rate of foam loss from this region
- Current testing efforts at MSFC and MAF should continue
- NASA should use knowledge gained from testing and analysis of the current LH2-IT flange geometry to redesign this area
  - Redesign efforts should include, but not be limited to, considerations of:
    - Minimizing the ability for nitrogens to come in contact with foam or SLA
    - Replacing the existing intertank nitrogen purge with a helium purge
    - Structural changes that eliminate or reduce all vent paths in the flange region

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**LN2 Collection Areas**

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**Stringer Vent Hole**

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ET – Foam Design – Certification

Stringers
Stringer Vent Path

Documentation:
- http://www.lockheedmartin.com/michoud/et/description.htm
- "Use of Shims in ET Flanges," presented at Michoud Assembly Facility, 10 Mar 03
- History of External Tank Foam Loss," RFI 00-000025
- Personal communication with Mike Javery, Lockheed Martin, Michoud Assembly Facility, 17 Apr 03
- "ET Bipod Ramp and Flange Dissection Out Briefing," presented at Michoud Assembly Facility, 15 May 03
ET - Foam Design - Certification

**Action / Issue:**
- Stringer valley cracks have been documented as occurring on super lightweights more frequently than on other tanks

**Background / Facts:**
- Cracks in the valleys between stringers (external stiffening elements) on the intertank have been observed on several missions on all types of tanks
  - Standard weight (eg. ET-4)
  - Lightweight (eg. ET-29 & ET-38)
  - SLWT
- However, the occurrence of these cracks has been identified more often beginning with the first SLWT, ET-95, launched with mission STS-91 in June 1998

**Findings:**
- Subsequent to the change to super lightweight tanks, final inspection teams started seeing cracks in the stringer valley areas more frequently than in lightweight or standard tanks
  - It is believed these cracks form during tanking as a form of stress relief at the aluminum ET cone and contractors
    - Hypothesis: thermal mismatched foam in these areas (part of the super lightweight design) is more susceptible to cracking
  - In particular, Team inspection & documentation procedures have not changed with respect to stringer valley cracks
  - Cracks are more difficult to spot in machined foam
- Thus, the sudden increase in the number of cracks observed with the advent of the SLWT appears to be real.
- A comprehensive review of historical records has not been performed
- However, a quick data search shows that these cracks were rarely recorded prior to the SLWT inception
- These cracks, if undetected in the bipod ramp, could provide a possible reservoir for LN2

**Recommendations:**
- NASA should continue tests currently underway at MSFC and MAF to understand cryopumping and cryoingestion
  - The tests involving full-scale mock-ups of the LN2-T should be monitored for the presence of stringer valley cracks
- NASA should plan to continue additional analysis and testing on the SLWT configuration to understand the cause of these cracks, their affects, and ways to prevent them from occurring
  - If these cracks are found to be detrimental, NASA should take steps to prevent them

**ET - Foam Design - Certification**

**Documentation:**
- Final Inspection InterTank Cracks Request for Information, RFI #81-000134
- Discussions with Armando Oliu, 24 March 2003
- Discussions at Michoud Assembly Facility, 02 April 2003
- Personal Communication, J. Feeley, Michoud Assembly Facility, 12 Jun-03
- E-mail, M. Quiggie, Michoud Assembly Facility, 19-23 Jun-03.
ET – Foam Production

2-1 Blowing Agent Changes
2-2 Manual Spraying Operations
2-3 Processing Environment Controls for Foam Applications
2-4 NDE for ET During Production
ET – Foam Production

- Documentation:
  - NASA's "Petition for Space Shuttle Program HCFC 141B Exemption Allowance," 4 Feb 03
  - "Blowing Agent into Splinter Meeting," presented @ MAF, 13 Mar 03
  - CAIB Request for information, "CAIB Cryosulation Report," 81-0001/27, 27 Mar 03
  - "Foam Blowing Agent," presented @ MAF 2 Apr 03
  - Public Hearing, "ET Cryosulation Report," 7 Apr 03
ET – Foam Production

- Action / Issue:
  - Manual spraying operations of complex and closeout areas are not sufficiently controlled
- Background / Facts:
  - Operators must be qualified to hand spray foam
  - Each spraying operation is unique and is operator dependent
  - Control of spraying variables has been limited except in the flange closeout area
  - Special techniques with limited qualified operators are now used due to prior problems in the flange closeout area
  - Spraying operations can be either one or two people depending on the operator's preference
  - Complex shapes and access to the area being sprayed makes these operations even more difficult to control

ET – Foam Production

- Findings:
  - Dissection of various bipod and flange closeout areas has revealed that defects are introduced during the spraying operation
  - Defects tend to occur in complex geometry regions or where there is limited access for operators during the spray evolution
  - Defects are random and unpredictable
  - There have been limited attempts to control spraying variables except in the flange closeout area
  - Summary: complexity of areas to be sprayed + variability in operator techniques = a unique product with insufficient unknown foam quality

ET – Foam Production

- Recommendations:
  - Efforts should be made to try and standardize (control) the hand spraying process as much as possible
    - If automated processes can be put in place to spray these areas, such as is currently done on the aircrane foam, every effort should be made to make that transition
    - In areas where hand spraying must continue, operators should be qualified to spray all complex geometries
    - There should be no foam application processes requiring less than two people

ET – Foam Production

- Documentation:
  - Personal observations at Michoud Assembly Facility (MAF), February – May 2003
  - Discussions with Lockheed Martin personnel, MAF, February to May 2003
  - Discussion with Marshall Space Flight Center/MAF personnel, 02 April 2003
  - ET Shredding – Composite Request for Information, RFI #B0-000026
  - ET-120 Dissection Outbrief, 10 April 2003

Complex spray areas around bipod fixture

Voids located in complex geometry areas
ET - Foam Production

**Action / Issue:**
- Process controls (especially those for temperature and humidity) may be insufficient to permit consistently high quality foam application.

**Background / Facts:**
- Spraying operations must be within required environmental conditions
- Boundaries of the environmental conditions are considered to be conservative to guarantee proper foam performance
- Plug pulls are performed subsequent to spraying operations to verify proper material bonding and strength

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**ET - Foam Production**

**Findings:**
- Most spraying operations occur at or near the outer acceptable boundaries of the processing envelope
- Large variability in the response of the foam based on inherent randomness of foam cell structure
- Plug pulls, as a single indicator, might not be sufficient to verify the foam's bonding and strength properties

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**ET - Foam Production**

**Recommendations:**
- Foam loss history should be looked at for correlation to processing environments and plug pull values
- The processing envelope should be reevaluated and attempts should be made to try and perform spraying operations more towards the center of the defined envelopes vice at the outer edges
- Plug pull requirements should also be reevaluated and the actual usefulness of these tests to determine overall foam application worthiness should be questioned
  - Localized plug values might not be telling the story for the whole tank

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**ET - Foam Production**

**Recent TPS Processing Data**

**Documentation:**
- CAIB Public Hearing - ET Cryoinsulation, Lee Foster and Scotty Sparks, 07 April 2003
- Discussions with Michoud Assembly Facility personnel, February 2003
ET - Foam Production

• Action / Issue: No validated NDE techniques are available to identify subsurface damage within ET foam during or after production.
• Background / Facts:
  - Extensive NDE is performed on welded aluminum sections of ET.
  - No NDE performed on ET thermal protection system (TPS) except:
    - Visual checks during and after production.
    - Eddy current checks for thickness.
    - Infrared acoustic inspections.
    - Plug pull & witness panel (destructive test).
  - Previous efforts at MAF (1986-93) were unsuccessful in identifying NDE technologies that could be readily implemented.
  - Boeing has had success using laser shearography on acreage foam of Delta-IV boosters, but geometry is much less complex than that of ET.
  - Inspection requirement is for larger defects.

Findings:

ET - Foam Production

• Findings: (cont.)
  - MAF and MSFC are actively pursuing development of an NDE technique to use on hand-sprayed closeouts.
    - Candidate techniques include: X-ray (radiography), backscatter X-ray, shearography, microwave, and terahertz.
    - Experts in field among are in Working Group A post-build & KSC processing inspections of the ET are visual.
  - No NDE is used to confirm or size regions needing repair.
  - Visual examination relies on experienced personnel.
    - Especially the IC/DEOS Team at KSC.
  - LTI (John Newman) has estimated that 12-24 months is needed to develop shearography scanner hardware for the ET.
    - Standards and procedures would also be required in addition to hardware.

ET - Foam Production

• Recommendations:
  - Potential Return to Flight Recommendation: NASA should continue to pursue the development, validation, and implementation of NDE techniques that can be used to interrogate ET foam during production.
  - NASA should continue to pursue the development, validation, and implementation of NDE techniques that can be used to interrogate ET foam following production (i.e. at KSC prior to launch).

Laser shearography in use on Boeing Delta IV boosters

NDE of 9” thick foam block revealed defects as small as 3” in diameter.

NDE of flat panels with intertank geometry yielded promising results.
ET - Foam Production

Limited correlation between shearography and bipod foam ramp dissections

- Shearography Indication
- Actual Defect
- Radiography Indication

Note: Data taken with limited experience base. Correlative analysis may be premature.

ET - Foam Production

Limited correlation between radiography and bipod foam ramp dissections

- Shearography Indication
- Actual Defect
- Radiography Indication

Note: Data taken with limited experience base. Correlative analysis may be premature.

ET - Foam Production

Typical foam defects not detected by laser shearography or radiography

- Rollover/Void
- Excessive Porosity

ET - Foam Production

Summary of MSCF/MAF NDE Efforts

Status as of 29 May 03

ET - Foam Maintenance

- All stud cracks
- Ice along Bipod/Flange union
- Stringer valley cracks

Defects in ET foam found by visual examination on launch pad

ET - Foam Maintenance

Unseen subsurface damage associated with visual surface defect in flat foam panels (Identified with laser shearography)
ET - Foam Production

Documentation:
- NSTS-8303, Rev. A, "Cosm Debris Inspection Criteria"
- (http://ww-launchopt.ssc.nasa.gov/medinfo/et/8303/TABLE%20OF%20CONTENTS.html)
- MMC-ET-RA13, "ET Project Nondestructive Evaluation Plan"
- MMC-ET-SE13, "ET Project Fracture Control Requirements and Implementation Document"
- MMC-ET-SE16, "ET Project Materials and Process Control Plan"
- E-mail, J. Newman (LTI Inc.) to J. Wolfe (CAIB), 10 June 03
ET – Foam Maintenance

3-2 ET Storage, Shipping, and Handling
3-4 Crushed Foam from Mate/De-Mate of ET-93
ET - Foam Maintenance

- **Action / Issue:** Foam crushed beneath the -Y (left side) bipod strut clevis during pre-launch mating & demating with the bipod strut may have contributed to the loss of the -Y bipod foam ramp from ET-93 during STS-107.

- **Background / Facts:**
  - ET-93 mated to SRBs on 8 May 02 in VAB, de-mated on 28 Aug 02
  - ET-93 mated to bipod on 24 Jun 02 in VAB; de-mated on 1 Aug 02
  - Operations carried out in accordance with standard procedures
  - Crushed foam seen after -Y strut removal (1.5" x 1.25" x 0.187")
    - Beneath -Y fitting clevis joint after bipod strut removed
  - Thickness of foam in this area: 2.197"
  - Excess crushed foam not permissible; Problem Report written
  - Testing was performed @ MAF and KSC (on ET-117) to determine:
    - If crushed foam on ET-93 could have caused loss of -Y bipod ramp
    - If limits specified in PR procedures were sufficient

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ET - Foam Maintenance

- **Findings:**
  - Crushed foam always present at ET bipod attach points
    - Specifically designed to be an "interference fit"
  - KSC engineers decided to defer action on PR. Rationale:
    - Crushed foam was contained beneath bipod strut clevis after mating to a new set of bipod struts
      - Unexposed (i.e., contained) crushed foam is permissible
  - Inspection of region after installation of bipod struts showed that crushed foam did not extend further than 0.75" beyond bipod fitting clevis joint
    - Within acceptable limits
  - STS-107 launched with crushed foam contained behind -Y bipod strut clevis

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ET - Foam Maintenance

- **Findings (cont.):**
  - Three other male-de-mate instances occurred on shuttle program; unknown link between mating/de-mating & foam loss
    - ET-13 used on STS-14(2)
      - No ingress to confinement foam loss
    - ET-23 used on STS-27R
      - Handhold skin integument bipod ramps not visible, no other loss noted
      - Mated & de-mated during checkout of Vandenberg AFB facilities
      - Extensive life damages due to the loss of SRB ablator during launch
    - ET-40 used on STS-80
      - Lost 2 rivets on flap under bipod
      - Lost one 10-inch diameter hole in intertank forward of -Y bipod ramp

---

ET - Foam Maintenance

- **Findings (cont.):**
  - Crushed foam testing conducted at MAF & KSC (on ET-117)
    - Red dye indicated extent of damage to be limited to a maximum of 0.5" beyond region visibly crushed with aid of dye
      - Within acceptable limit
    - Re的地方 service airflow with bipod strut installed
    - Undamaged foam thickness was over 2" on ET-117
    - No contrast potential
    - Localized damage would have no impact on performance of ramp
    - Results indicate no contribution from crushed foam to the loss of the bipod foam ramp on ET-93

- **Recommendations:**
  - None

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ET - Foam Maintenance

- **Problem Report (PR ET-93-ST-003):**
  - Description of damage and corrective actions taken
  - Safety implications and future mitigation strategies

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ET - Foam Maintenance
Problem Report (PR ET-93-ST-003)

ET - Foam Maintenance
Problem Report (PR ET-93-ST-003)

ET - Foam Maintenance
Crushed Foam on ET-93 Revealed After Removal of -Y Bipod Strut

ET - Foam Maintenance
Crushed Foam Region on ET-93 Contained by Installed -Y Bipod Strut

ET - Foam Maintenance
Results of Crushed Foam Testing on ET-117 @ KSC

ET - Foam Maintenance

Documentation:
- E-mail message from Jim Fleser, Lockheed Martin, Michoud Assembly Facility, 04-26-2003
- "Production Info – Splitter Mating," presented at Michoud Assembly Facility, 03-15-2002
- TPSR ET-93-ST-003, "Bipod Strut Removal," 03-01-2002
- PR ET-93-ST-00013, "There is An Area Of Crushed Foam From The Installation Of The J-Y," 04-09-2002
- http://www esa.int/esaCP/CP-9900128en.html
- Meeting with John Biele, USA Engineer, Kennedy Space Center, 05-10-2003
- 8051 10/10/920-500, Lockheed Martin, "BIPOD INSTL,ET ORB,FM/0"  
- STD-ET-Correlation.xls, from Jim Fleser, Lockheed Martin, Michoud Assembly Facility, 04-04-2003
- Mission Support Room Log Board located at Michoud Assembly Facility
- "Crushed Foam Testing," response to RFI 81-000056
ET - Foam Maintenance

ET-93 Processing Timeline at KSC

Examples of Areas Requiring Post-Build Rework

Clip embedded in ET-111 Intertank Stringer

Two areas of crushed foam on ET-103 LH2 barrel, impact from fire bell in VAS

Surface voids in the ET/5BB aft fairing splice plates foam doublers on ET-111

ET - Foam Maintenance

- Documentation:
  - MMC-ET-SE42, External Tank Long Term Storage Requirements
  - MMC-ET-SE06b, MMC-ET-7MBw, External Tank Storage and Pre-Shipments Test Specification Requirements
  - SP 84-6-1, Manufacturing Handling Plans (NHP)
  - NTS 08171, File IV
  - Product Assurance Procedure 17.11.5
  - "Post-Build Storage, Shipping, and Handling," presented at MAF, 2 Apr 03
  - Personal Observations at Michoud Assembly Facility, 11 Apr 03
  - Personal Communication with Amanda Chu, at Kennedy Space Center, 10 Mar 03
  - http://msf.msfc.nasa.gov/IMAGES/MEDIUM/8216121.jpg
  - http://www-jk.ksc.nasa.gov/PublicInfo/ET/ETPhotoBook/LOAD/Offload.htm
  - Mission Support Room Log Book, Michoud Assembly Facility
  - "ET Processing Review," presented during Working Scenarios Meeting at JSC by M. Loonard 27 May 03
ET – Foam
Launch – Ascent

4-1 Cryopumping
4-2 ET Foam Loss History
4-3 Aerodynamic Loads on the Bipod Ramp
4-4 Foam Loss Related to Weather
4-5 Water Absorption by ET Foam
ET - Foam
Launch - Ascent

- **Action / Issue:** Cryopumping & Cryoingestion
- **Background / Facts:**
  - Cryoingestion: escape of N2 from intertank into SLA or foam
  - Gaseous N2 used to purge inner tank condenses to liquid on upper surface of LH2 tank
  - LH2 can leak through LH2-intertank flange shims, panel joints, and vent holes at strainers
  - LH2 can then enter voids in foam or can be absorbed by SLA
  - Cryopumping: entry of ambient air through cracks in foam
  - Type (2): Ambient air condenses on surface of LH2 or LH2 tanks
  - Air comes into contact with tank surface through cracks in foam
  - Air can then enter voids or debonds at foam/substrate interface
- **Theory:**
  - Trapped liquid N2 or liquid air vaporizes during ascent as temp rises
  - Lacking an escape path, vaporization causes a pressure build-up
  - Pressure can force foam to shed off of the ET

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**ET - Foam
Launch - Ascent**

- **Findings:**
  - Recent dissections of bipod ramps and LH2-intertank flanges (ET-94, ET-120, ET-124) revealed flaws (voids, debonds, FOD) - potential cryoingestion/cryopumping sites
  - Cracks in intertank stringer valleys & other areas may contribute to cryopumping
  - No evidence exists of SLA having spalled off along with foam
  - Test #6 at MSFC (cryoingestion) revealed:
    - When conditions were correct for cryoingestion and subsequent vaporization, foam failure mode was characterized by cracking
    - Cracking relieved pressure permitting N2 to escape from beneath foam
    - No spalling of foam was observed
  - Test #6 conditions do not simulate the operational environment

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**ET - Foam
Launch - Ascent**

- **Findings (cont.):**
  - Test #2 at MSFC (combined thermocryovacuum environment) revealed:
    - Conditions during tanking favor the formation of liquid and/or solid N2 in "Y" joint at intertank flange
    - Conditions are not correct for vaporization of liquidsolid N2 during ascent
    - MSFC will continue to change parameters on Test #2 to determine if N2 vaporization can be artificially induced
    - Bottom Line: Vaporization following ingestion of N2 from the intertank may be a contributing mechanism for foam loss but does not appear to be the sole driver

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**ET - Foam
Launch - Ascent**

- **Recommendations:**
  - NASA (MSFC) should continue with the series of tests planned to investigate the loss of the bipod foam ramp from ET-93 during STS-107
    - These tests will focus on understanding the cryopumping/ingestion issue and its effect on and relationship to other environmental conditions that the ET experiences during launch and ascent.
  - NASA should perform independent (non-MSFC) testing to understand cryo-effects and other foam properties/behavior
  - Lessons learned from these tests must be used in the redesign of the bipod fitting endosoure and also in the redesign of the LH2-intertank flange area
  - Cryopumping and cryoingestion must be eliminated as potential initiating events for foam loss from the ET.
ET - Foam Launch - Ascent

Theoretical Progression of LN2 Cryoingestion from Intertank

- Liquid Nitrogen (LN2)
- Solid Nitrogen

Typical Voids found during Dissection of ET-120 +Y Bipod Ramp

Potential Cryoingestion Paths

ET - Foam Launch - Ascent

Bipod Thermal/Vacuum Cryogenic Test MSFC Test #2

Description
- Replicate the TPS configuration of the +Y bipod ramp and expose this area to simulated ground and flight environments in an attempt to replicate the probable scenario of foam loss similar to that experienced on STS-112

Objective
- Characterize TPS debris from bipod area resulting from the following ascent environments
  - Cryogenic back-face temperatures coupled with on-pad soak duration
  - Back-face temperature ascent profile
  - Ascent pressure profile
- Characterize configuration of hardware and SLA-961 remaining after initial foam loss/Results support fault tree blocks relating to foam loss and the impact

ET - Foam Launch - Ascent

Cryointegration/Cryopumping Fundamental Data Test MSFC Test #3

- Description
  - Collect fundamental phenomenon investigation for the effects of cryo fluids on stacked structure and TPS configurations
- Objective
  - Bridge testing results from small single material test articles to interaction effects of SLA with SOF in controlled tests where specific fundamental characteristics may be observed and quantitatively evaluated for use in modeling the behavior of complex SLA and SOF structures
  - Investigate SLA foam debris liberation sensitivity to geometry
  - Characterize failure modes
  - Characterize cryopumping sensitivity to crack size
  - Investigate freezing effects of cryopumping
  - Investigate rate effects of ingestion and venting
  - Investigate cryopumping behavior to configuration
  - Investigate pressures induced failure of SLA foam
  - Investigate phenomena identified by the TEF
ET – Foam
Launch – Ascent

- Documentation:
  - "External Tank Working Group Test Approval Request" presented to CAIB, 25 Feb 03
  - "Technical Exchange Forum on External Tank Nonmetallic Debris," MSFC, 3-4 Mar 03
  - "External Tank Working Group - Testing" presented at MAF, 14 Mar 03
ET - Foam
Launch - Ascent

- **Action / Issue:** The ET has shed foam since STS-01. Major events, such as the loss of portions of bipod foam ramps, have occurred periodically.
- **Background / Facts:**
  - Although tile damage is often used as the indicator of foam loss, no conclusive evidence exists linking tile damage with foam loss.
  - Chemical sampling of tile damage sites for foam has been inconclusive.
  - Debris sources are not limited to the ET.
  - Use of imagery from launch, ascent, and ET separation is necessary to confirm foam loss.
- All 113 STS missions have been reviewed to determine availability of launch/ascent imagery data.
- No imagery coverage available on 34 missions.
- 16 Night Launches & 18 Day Launches with no camera coverage.
- Bottom line: Presence or absence of foam loss can be visually confirmed on 79 of 113 missions at this time.

ET - Foam
Launch - Ascent

- **Findings:**
  - 65 missions experienced visually confirmed foam loss.
  - Foam loss confirmed in 82% of missions for which imagery was available.
  - 55 experienced loss of foam from U/D-Interlink flange.
  - 34 experienced loss of foam from Interlink screws.
  - At least 7 experienced loss of a portion of a bipod ramp (all Y/206).
  - 12 experienced confirmed loss of foam from thrust panels ("popcornings").
  - 45 experienced loss of foam from other sites.
  - Of the 57 without a bipod ramp loss, 59 experienced losses "near bipod".
  - Worst damage to orbiter tiles: STS-27R (OV-104).
  - Due to loss of SRB ablator material and due to loss of ET foam.
  - Hits to orbiter: 644 lower surface (272+1) (707 total (298+4)).
  - Most damage to tiles from ET foam loss: STS-87 (OV-102).
  - Thrust panel popcornings.
  - Hits to orbiter: 244 lower surface (109+1) (308 total (132+4)).

ET - Foam
Launch - Ascent

- **Findings (cont):**
  - MSFC has taken actions on numerous occasions to eliminate or reduce foam loss from the ET.
  - NASA must continue testing currently underway at MSFC and MAF to identify the root cause(s) for the generation of debris from the ET.
  - NASA must minimize the generation of debris from the ET.
  - NASA must establish programs to understand the possible damage resulting from debris impacts on other Space Shuttle elements.
  - NASA must institute a policy to provide (visual) imagery on 100% of launches to check for ET foam loss and other launch debris.

ET - Foam
Launch - Ascent

- **Recommendations (cont):**
  - NASA must harden each of the Space Shuttle elements (especially the orbiter) to maximize their impact damage tolerance.
  - NASA should take an integrated approach to address these recommendations.
  - All future efforts that minimize the debris generated by each Space Shuttle element and maximize each element's impact damage tolerance must be mutually compatible.
  - NASA should consider eliminating a foam-covered ET from the Space Transportation System.

ET - Foam
Launch - Ascent

**Loss of -Y Bipod Ramp Foam, STS-7 (OV-99, ET-6)**

**Loss of -Y Bipod Ramp Foam, STS-32R (OV-102, ET-32)**
ET – Foam
Launch – Ascent
Loss of – Y Bipod Ramp Foam, STS-50 (OV-102, ET-43)

ET – Foam
Launch – Ascent
Loss of – Y Bipod Ramp Foam, STS-52 (OV-102, ET-55)

ET – Foam
Launch – Ascent
Loss of – Y Bipod Ramp Foam, STS-62 (OV-102, ET-62)

ET – Foam
Launch – Ascent
Loss of – Y Bipod Ramp Foam, STS-112 (OV-104, ET-115)

Summary of Some ET Project Office Efforts to Reduce Debris Shed by External Tank

Documentation:
- CAIB Request for Information, “External Tank Foam Loss,” B1-00039
- MAF Mission Support Room Log Board, Michoud Assembly Facility
- http://www.nasa.gov/centers/oceoon/homepage.html (sight launches)
- STS-ET Correlation.xls, from Jim Foley, MAF
- CAIB Request for Information, “CAIB Cryogenic Report,” B1-000121
- CAIB Request for Information, “Discussions at MAF Today,” (w/ Scotty Sparks & Steve Holmes), B1-000132
- “The Chemical Analyses,” Discussion & E-mail with Jorge Riveras@ MAF, 19 Apr 03
- “ET Cryoinulation,” presented at the CAIB Public Hearing, L. Foster & S. Sparks, 7 Apr 03
Ascent Debris Strike Other (ET/Foam)

- **Action / Issue:** Complex aerodynamic loads on ET-93's bipod foam ramp may have caused it to fail during the ascent of STS-107.
- **Background / Facts:**
  - Bipod foam ramp shed at 81 sec (Mach 2.48, $\alpha = 2.08^\circ$)
  - Ascent environment is very severe; flow field is complex
  - 3 interacting shocks occur in bipod region
  - Airloads determined by numerous methods
    - Wind tunnel testing of 3% scale model
    - Computational Fluid Dynamics (CFD) analysis
    - Analytical (Howerer) analysis

**Findings:**
- Early wind tunnel tests on flat-faced and 20° angle ramps confirmed a 1.1 safety factor against failure caused by aerodynamic loads.
- Additional analysis calculated a safety factor of 3.95
- Wind tunnel testing was not performed on the current bipod ramp geometry (22°-30°) nor on flight configuration articles (SLA, underlying bond filing, etc.)
- Wind tunnel testing was also performed on a 3% scale model of Space Shuttle
- Correlation between this testing and CFD-analytical models was good
- MADS data from the OEX recorded recovered from STS-107 confirmed that CFD and analytical models were conservative
- No flight instrumentation was used on early ETs to investigate airloads on bipod ramps
- Instrumentation on early flights collected only bipod strut strains

**Findings (cont.)**
- Aerodynamic loads predicted by CFD and analytical methods are significantly less than design requirements
  - Minimum safety factor is 1.4
- Vibroacoustic analysis calculated a safety factor of 1.64 against the formation of divots
- No finite element analysis was performed to determine the ability of the bipod foam ramps to withstand aerodynamic loads
  - Complexity of geometry and material makes such modeling difficult
  - Efforts are in place at NASA to develop a finite element modeling capability for foam protrusions
- The complex combined aerotherm/vibroacoustic/vacuum/acoustic is extremely difficult to simulate, thus, combined testing was never performed
- "Worst case" conditions were solved and superimposed to determine the integrity of the bipod foam ramps under these conditions

**Recommendations:**
- NASA must continue to improve its capabilities to perform analytical and numerical simulations of the complex combined environments to which the ET is exposed.
  - These capabilities must be validated with test and/or flight data

Ascent Debris Strike Other (ET/Foam)

**STS-107 Trajectory Reconstruction M-08-024**

Flowfields
Ascent Debris Strike Other (ET/Foam)

Pressure Coefficients \( (C_p) \)

- \( M_\infty = 6.99 \)  \( \alpha = -1.7^\circ \)
- \( M_\infty = 1.06 \)  \( \alpha = -3.91^\circ \)
- \( M_\infty = 2.46 \)  \( \alpha = 2.08^\circ \)

Flowfields \( \rightarrow \) Y Bipoled Region

(JSC CFD
Mach no. = 2.46
Alpha = 2.08°)

Ascent Debris Strike Other (ET/Foam)

Pressure Coefficients \( (C_p) \) in \( \rightarrow \) Y Bipoled Region

(Coordinates in \( \rightarrow \) Y bipoled region inaccurate due to simplifications in model)

- Observations
  - 3 intersecting shocks in bipoled region
  - Complex flow features
    - Separated flow
    - Vortices ahead of bipoled/ET ramp
  - Significantly more complex local flow field than lower Mach numbers
  - Complex flow characteristics begin at approximately Mach = 1.4

Original Bipod Ramp Wind Tunnel Test Components

Ascent Debris Strike Other (ET/Foam)

Comparison of Wind Tunnel Test Data With CFD Predictions

for Pressure Coefficients Longitudinally Along the ET Surface

- CFD Prediction
- Wind Tunnel Test Data

Path Along Which Data Was Taken and CFD Prediction Was Made

Ascent Debris Strike Other (ET/Foam)

Predicted Side \( (Y\text{-direction}) \) Forces on ET-93's Y Bipod Foam Ramp During STS-107

Report Volume V October 2003
### Ascent Debris Strike

#### Other (ET/Foam)

**Predicted Biped Foam Ramp Aerodynamic Loads**

<table>
<thead>
<tr>
<th>Axis</th>
<th>Design Requirements (lb)</th>
<th>CFD predictions of Flight Loads</th>
<th>Mach 0.96</th>
<th>Mach 1.06</th>
<th>Mach 2.46</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Axial Load (+/0°)</td>
<td>899.4</td>
<td>254</td>
<td>637</td>
<td>48</td>
<td></td>
</tr>
<tr>
<td>Max Side Load (+/-15°)</td>
<td>756.2/-2483.5</td>
<td>-359</td>
<td>-664</td>
<td>-24</td>
<td></td>
</tr>
<tr>
<td>Max Radial Load (+/-15°)</td>
<td>1409.3</td>
<td>-332</td>
<td>-24</td>
<td>322</td>
<td></td>
</tr>
</tbody>
</table>

Includes Safety Factor of 1.5

Predictions indicate Aerodynamic Loads Are Less Than Design Limits

**Documentation:**
- "Biped Airflow and Loads," presented by R. Gorman, RFI B1-000050, 23 Mar 03
- "ET Biped Aero Ramp Foam Verification / Certification," presented by M. Quiggle, at Michoud Assembly Facility, 10 Apr 03
- "Ascent CFD Verification," RFI B1-000147, 22 Apr 03
- Personal Communication, M. Quiggle, at Michoud Assembly Facility, 15 May 03
- "1.1.1 TPS Debris Fault Tree Closeout Briefing," S. Sparks at MSFC, 20 May 03

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### Absolute Angle for Flights at 39° Inclination
ET – Foam
Launch – Ascent

- **Action / Issue:** Potential for Foam Loss to be Related to Weather
- **Background / Facts:**
  - Numerous suggestions (via FIAs and media) that foam loss is related to moisture absorption and/or ice formation
  - Weather office at KSC has provided the following historical info for the time during which the shuttle was outside for each mission:
    1. Daily rainfall
    2. Max/min daily temps
    3. Max/min daily wind
    4. Max/min daily atm pressure
    5. Temp at start of tanking (fueling)
    6. Temp at launch
- **Findings:**
  - Average ET pre-launch exposure time for all missions is 38.5 days
  - ET-03 (used on STS-107) was on the pad for 39 days prior to launch
  - No apparent trend linking pre-launch exposure time to foam loss
  - No apparent trends linking foam loss with any other variables analyzed

---

ET – Foam
Launch – Ascent

- **Recommendations:**
  - NASA should continue to investigate moisture absorption by foam and relate any results to pre-launch exposure of the ET to the atmosphere.
  - NASA should continue analyzing weather data in search of correlations between weather variables and foam loss. Particular attention should be given to identifying the importance of combinations of variables that might contribute to foam loss.
- **Documentation:**
  - RFI B1-00145 “Historical Weather Data,” 27 Mar 03
  - John Madura, KSC Weather Office, 321-867-0814, john.l.madura@nasa.gov
ET - Foam
Launch - Ascent

- Action / Issue: Moisture absorption by the external tank (ET) foam may have caused or exacerbated the foam loss event by increasing the mass of the piece shed from ET-93 during the ascent of STS-107

- Background / Facts:
  - PSA #644 cited a "review of publications" indicating closed-cell foam can absorb water and increase in mass by a factor of 10
  - B. Peterson (formerly of Texas Chemical) cited experience with polyurethane foams that could absorb water at near-frozen temperatures if chemical constituents of foam were correct
  - Prof. L. Glicksman (MIT) performed preliminary calculations
    - Snowed water vapor could be absorbed into foam at 68°F and 100% m
    - 8-hour tanking would result in absorption of 0.001 lb/ft³ of water
  - Moisture absorption by foam is a concern in the building industry
  - PSA #671 identified two commercially available foams designed to predict moisture absorption in foam
  - Incorrect analyses by media led to public misunderstandings

- Findings:
  - ET foams do not have chemistry susceptible to moisture absorption
    - Peterson identified a specific EO/PO ratio (ethylene oxide / propylene oxide) that made foams absorptive near 30°F
    - ED is the hydrophobic component (attractive to water)
    - EO/PO ratio of ET foams is zero
  - Regardless of chemistry, unlikely that closed-cell foam can absorb liquid water
    - Diffusional absorption of water vapor may be possible
    - Prof. Glicksman predicted ice and vaporization layers
    - Potential ice layer: thickness = 0.002 in, weight = 0.015 lb/ft²
    - Vaporization layer: thickness = 0.2 in, weight = 0.06 lb/ft²
  - Dr. Osheroff has performed simple experiments at Stanford
    - Immersion of foam in ice water suggests water permeates foam only to 0.004 in below surface
    - Consistent with depth of single layer of open cells at surface

- Findings: (cont.)
  - MSFC previously performed water absorption tests under accelerated conditions (7 days at 129°F and 95% m)
    - NCFI 24-124 average foam, 0.12% weight gain
    - BX 250 closed-cell foam, 0.16% weight gain
    - SS 171 fieldline foam, 0.42% weight gain
    - PDL 1034-poured foam, 0.03% weight gain
  - Both foams had machined surfaces (i.e. surface cells were open)
  - Recent additional tests conducted at MSFC (with Prof. Leon Glicksman of MIT, retained as a consultant)
    - Immersion of BX 250 & NCFI 24-124 in distilled, de-aired water at 129°F for over 60 hours
    - Water absorption equivalent to thickness of exposed surface layer of open cells
    - Consistent with Dr. Glicksman's calculations and Dr. Osheroff's experiments

- Group Recommendations:
  - NASA should consider continued testing per Dr. Glicksman's suggestion
    - Investigating water ingress through unique features (long voids, etc.)
    - Developing failure mode model incorporating test results

ET - Foam
Launch - Ascent

- Findings: (cont.)
  - Recent additional tests conducted at MSFC (cont.)
    - Vapor Phase Transmission through BX 250
      - Included thermal gradient of ~70°F to simulate tanking conditions
      - Level of transmission deemed insignificant (< 3 g/hr m²)
    - Especially in light of low moisture absorption & limited tanking times
    - Bottom Line from recent tests at MSFC
      - "Absorbed" water limited to open cells on surface
      - Any water absorbed deeper into foam does not affect transmission at a very low rate
      - Water ingress through voids/cracks open to surface and subsequent vaporization & crack formation or growth is a possibility
    - Role of long voids, wormholes, knottiness may merit further testing
    - Future research should integrate test results into a mechanistic, quantitative failure mode model

ET - Foam
Launch - Ascent

- Types and Locations of ET Foams

ETA - Foam
Launch - Ascent

- Types and Locations of ET Foams

ET - Foam
Launch - Ascent

- Types and Locations of ET Foams

ET - Foam
Launch - Ascent
ET - Foam Launch - Ascent

**Types of ET Foams**

<table>
<thead>
<tr>
<th>Type</th>
<th>% of Total</th>
<th>Application Areas</th>
<th>Application Process</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>NCFI 24-124</td>
<td>(7%)</td>
<td>Liquid, foam, spray</td>
<td>Automatic Spray</td>
<td>Isocyanurate</td>
</tr>
<tr>
<td>BX 250</td>
<td>(14%)</td>
<td>Liquid, foam, spray</td>
<td>Manual Spray</td>
<td>Urethane</td>
</tr>
<tr>
<td>NCFI 24-07</td>
<td>(7%)</td>
<td>Liquid, foam, spray</td>
<td>Automatic Spray</td>
<td>Isocyanurate</td>
</tr>
<tr>
<td>PDL 1034</td>
<td>(1%)</td>
<td>Liquid, foam, spray</td>
<td>Foam/Metal</td>
<td>Urethane</td>
</tr>
</tbody>
</table>

**Moisture Absorption by ET Foams**

- **NCFI 24-124**
  - Accelerated Exposure (7 days @ 125°F and 95% humidity)
  - 0.12% weight gain due to moisture absorption (machined foam)
  - 0.75% maximum weight gain due to moisture absorption (after 5 days)
  - 0.04% moisture gain after 28 days

- **Vented NCFI 24-124**
  - Concern: Holes in vented foam will wick moisture if ET is exposed to rain.
  - Test performed: 5 repeated exposures of heavy rain and extreme freezing conditions caused no deterioration of the foam's tensile properties.

ET Foam Moisture Absorption (cont.)

- **BX-250**
  - Accelerated Exposure (7 days @ 125°F and 95% humidity)
  - 0.16% weight gain due to moisture absorption (machined foam)

- **SS-1171**
  - Accelerated Exposure (7 days @ 125°F and 95% humidity)
  - 0.42% weight gain due to moisture absorption (machined foam)

- **PDL-1034**
  - Accelerated Exposure (7 days @ 125°F and 95% humidity)
  - 0.83% weight gain due to moisture absorption (machined foam)

**Conclusion**

- ET foam materials absorb insignificant amount of moisture under accelerated test conditions.

**Documentation:**
- E-mail: Bruce Peterson to Johnny Wolfe, 27 Feb 03
- E-mail: Leon Glickerman to MG Barry, 6 Mar 03
- CAIB Request for Information, "External Tank Moisture Absorption," B3-00060
- CAIB Request for Information, "ET Cryoinsulations," B1-000121
- PIA 671 "Insulation & Moisture"
- PIA 644 "Closed Cell Foam Can Absorb Water"
- Discussion with Scotty Sparks (MSFC) at MAF, 16 Apr 03
- Discussion with Dr. Osheroff (CAIB/Stanford) at MAF, 21 Apr 03
- Response to PFT/FT-00190 "ET Foam Moisture Absorption Testing," 1 Jun 03
RCC
Design – Certification

5-1  WLE Subsystem Design Requirements and Certification
5-2  RCC Impact Energy Requirements and Certification
Wing Leading Edge Design & Certification

- **Action / Issue:** Determine adequacy of the WLE subsystem requirements, design and certification

- **Background / Facts:**
  - RCC is a critical component of the TPS (safety-of-flight)
  - Performance and design requirements documented in specification MU070-0001-1E, 7 Nov 02
    - TPS impact energy design requirement is 0.006 foot-lbs (paragraph 3.3.1.6.11)
    - Orbiter not designed to withstand launch debris or ice (paragraph 3.3.1.6.16)

Wing Leading Edge Design & Certification

- **Background / Facts:**
  - Procurement specification MC521-0007, Rev E requirement more stringent than design requirement
  - Impact/ground handling damage resistance limits defined in figure 3.1
  - Impact energy limit ranges from 1 to 2.25 foot-pounds based on part thickness
  - TPS mission life requirement of 100 missions with scheduled maintenance and refurbishment (paragraph 3.4.3)

Wing Leading Edge Design & Certification

- **Background / Facts:**
  - RCC system is mounted to the wing front spar using attach fittings bolted to the front spar
  - Wing front spar attach fittings redesigned from a 2-piece design using A-266 steel (OV-102) to a 1-piece design using Ti-6Al-4V titanium (subsequent orbiters)
  - The insulators used to protect the metallic components of the WLE have been redesigned to increase survivability against MMD
  - Moment constraint fittings (spanner beams) were retrofitted on several OV-102 RCC panels as a result of an increase in the predicted loads
  - OV-102 spanner beams installed on panels 5 through 19

Wing Leading Edge Design & Certification

- Various Insulators
  - Front Spar Fittings

**OV-102 RCC Panel 3 on Right Side**
Wing Leading Edge Design & Certification

RCC T-Seal
Spanner Beams
RCC Panel

Wing Leading Edge Design & Certification

Spanner Beam
RCC Panel
Insulators

Wing Leading Edge Design & Certification

All T-Seal Lugs Have Thickness = 0.325" (25 Plies)
Typical T-Seal

Wing Leading Edge Design & Certification

Thickness is 0.247"
Typical T-Seal Edge

Wing Leading Edge Design & Certification

2219 or 6061 Aluminum
A-286 Steel Bolts
LI2200 Tile
Typical Lower Carrier Panel

- Background / Facts:
  - RCC developed to withstand the high temperature environment for multiple missions and maintain aerodynamic shape
  - RCC composed of Carbon-Carbon substrate to carry the load
  - RCC outer surface converted to Silicon-Carbide (SiC) coating to provide oxidation resistance to the carbon substrate
  - RCC substrate porosity filled using tetraethyl orthosilicate (TEOS)
  - Type A coolant applied to seal SiC coating crazing cracks
  - Double Type A (DTA) sealing process developed to improve mission life and involves additional TEOS and Type A application process
Wing Leading Edge Design & Certification

- Minimum WLE RCC Thickness

- Findings (agreed to by Curry, Gordon, Grant):
  - Impact of aging in terms of calendar time on corrosion, adhesive breakdown, etc. and impact to structural integrity must be determined
  - Safe-life design approach used for RCC mission life which is potentially an unsafe approach to ensure structural integrity
  - The residual strength of damaged RCC parts has not been demonstrated by testing with the exception of substrate oxidation, pinholes and craze cracks

Wing Leading Edge Design & Certification

- Recommendations (agreed to by Curry, Gordon, Grant):
  - Determine RCC component damage sources, frequency, and severity to include debris impact during ascent
  - Determine the damage tolerance capability for each damage type, location, and size ranges by calculating remaining service life and residual strength
  - Develop an NDE technique and capability to ensure damage limits have not been exceeded prior to each mission
  - Establish realistic service life duration expectation for remaining orbiters and revise operation and maintenance requirements accordingly

Wing Leading Edge Design & Certification

- Documentation:
  - Briefing by D. Curry et al., "Orbiter RCC Design and Flight Experience", 28 July 1999
Wing Leading Edge Design & Certification

- **Documentation:**
  - Paper by D. Curry, "Thermal Protection Systems Manfred Spacecraft Flight Experience", February 1992
  - AFITC-TR-85-11, "Flight Test Results from the Entry and Landing of the Space Shuttle Orbiter for the First Twelve Orbital Flights", June 1985
  - Paper by D. Curry et al., "Space Shuttle Orbiter Leading Edge Flight Performance Compared to Design Goals", March 1983
  - Rockwell Report 5D73-511-0308B, "Orbiter Leading Edge Structural Subsystem Induced Environments", 9 April 1976
**RCC Impact Energy Requirements**

- **Action / Issue:** Determine adequacy of RCC impact requirements and certification
- **Background / Facts:**
  - Performance and design requirements documented in specification MU73-0001-1E, 2 Nov 02
  - TPS impact energy design requirement is 0.006 foot-lbs (paragraph 3.3.1.8.11)
  - Orbiter not designed to withstand launch debris or ice (paragraph 3.3.1.8.16)
  - Procurement specification MC621-0057, Rev E requirement more stringent than design requirement
    - Impact energy limit ranges from 1 to 2.25 foot-pounds based on part thickness

---

**Previous RCC Impact Testing**

- **Background / Facts:**
  - Hypervelocity impact testing performed
    - Reference NASA-LARC Report TMX-74039, June 1977
    - Nylon projectile resulted in front face damage at 2.2 foot-pounds and both front and back face damage at 8.1 foot-pounds
    - Glass projectile resulted in front face damage at 0.2 foot-pounds
  - Hypervelocity impact testing performed in support of NRC MMOD study at JSC facility
    - 15 shots using 2017-T4 aluminum
    - Projectile energy ranged from 53 to 213 foot-pounds
    - Minimum damage: front face = 0.65" and back face = 0.87"

---

**WLE RCC Impact Fleet Experience Summary**

<table>
<thead>
<tr>
<th>Year</th>
<th>STS</th>
<th>OV</th>
<th>Flight</th>
<th>Impact Location</th>
<th>Debris Type</th>
<th>Resulting Damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>27R</td>
<td>104</td>
<td>3</td>
<td>T-318 FR</td>
<td>SRB Ablative</td>
<td>1 Dent, No SIC Loss</td>
</tr>
<tr>
<td>1992</td>
<td>45</td>
<td>104</td>
<td>11</td>
<td>Panel 10R</td>
<td>Man-Made Object</td>
<td>2 Dents w/ SIC Loss</td>
</tr>
<tr>
<td>1994</td>
<td>55</td>
<td>102</td>
<td>17</td>
<td>Panel 11L</td>
<td>WACG</td>
<td>Small Crater</td>
</tr>
<tr>
<td>2003</td>
<td>107</td>
<td>163</td>
<td>38</td>
<td>Panel 5 to 10</td>
<td>ET Bi-Pod Foam</td>
<td>Under Evaluation</td>
</tr>
</tbody>
</table>

21 Flights sampled, 43 Impacts Discovered due to Orbital Debris, Largest Damage = 9.2".

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**WLE RCC Impact Fleet Experience Foam/Ablative**

- **Background / Facts:**
  - OV-104-03 impact damage to right wing discovered after STS-27R in 1988
    - Reference TPS post-flight report KLO-89-001
    - "Some of the RCC panels and teas seals had streaks on the OML"
    - "Rib station 07 had a dent near the upper trailing edge"
    - Most probable cause is the right SRB nose cap ablative insulating material
    - OV-102-26 ET bi-pod ramp foam impact to left wing during STS-107 in 2003

---

**WLE RCC Impact Fleet Experience Man-Made Object**

- **Background / Facts:**
  - OV-104-11 impact damage to panel 10R discovered after STS-45 in 1992
    - Reference S. Christensen briefing
    - Substrate was exposed and oxidized, panel scrapped
    - Failure analysis documented in LTR4068-2427
    - Impact was caused by a low velocity impact by a man-made object
    - Impact occurred before reentry heating
    - Ascent encounter determined to be possible
    - On-orbit encounter determined to be remote possibility
WLE RCC Impact Fleet Experience

**Man-Made Object**

- OV-104-11, Panel 10R Impact Damage (1992)

**MMOD**

- Background / Facts:
  - OV-102-17 impact damage to panel 5L discovered after STS-65 in 1994
  - Most likely cause is a micro-meteorite (MMOD)
  - Hypervelocity impact to RCC components during flight is not unusual
  - 43 impacts occurred during the 21 flights sampled
  - Largest damage was 0.2"
  - No through-penetrations occurred

- OV-102-17, Panel 5L Micro-meteorite (1994)

- Findings (agreed to by Curry, Gordon and Grant):
  - Impact energy requirement is minimal
  - Impact energy capability exceeds original design requirements

- Recommendations (agreed to by Curry, Gordon and Grant):
  - Utilize foam impact test results to evaluate impact energy resistance and adequacy of current requirements
  - Establish realistic launch/vehicle debris types (foam, SLA, etc.) and evaluate capability of WLE system to withstand the impacts via testing and analysis

**Documentation:**

- Boeing report KLO-03-001, Mission STS-112 OV-104 Flight 26 Thermal Protection System Post-Flight Assessment, May 2003

WLE RCC Impact

**Category: Potential Contributor**

- Crater Approximately 0.08" in Diameter
- Depth Unknown but Reported not to be through-thickness

WLE RCC Impact

**Documentation:**

- Paper by D. Curry et al., “Oxidation of Hypervelocity Impacted RCC”, June 2003
WLE RCC Impact

- Rockwell Report LTR4068-2427, "Investigation of RCC RH Panel #10 Wing Leading Edge Impact Damage STS-45 (OV-104), September 1992
- Rockwell briefing by S. Christensen, "Investigation Analyses of the RCC RH Panel #10 Impact From STS 45 (OV-104), 2 July 1992
- Rockwell Report, "Evaluation of Flight Experience and Test Results for Impact on Orbiter RCC and ACC Surfaces", 26 November 1984
- NASA-LARC Report TMX-74295, June 1977

112
6-1 RCC Production Processes
RCC Production

- **Action / Issue:** Determine adequacy of RCC production process
- **Background / Facts:**
  - Continuous production since 1973
  - RCC component manufacturing flow days = 6 months
  - Currently only limited production capacity exists due to low demand for parts
  - RCC part deliveries = 943 to date
  - Production of 7 T-Seals, 1 Chin Panel and 2 Panel/T-seal assemblies in work
  - NDE is performed after initial part cure and after the final pyrolysis cycle
  - Ultrasonic NDI is performed after the same processing steps and after the SIC coating process
  - Control panels are fabricated in parallel with RCC part production

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RCC Production

**RCC Paper Review Summary**

- Documents were reviewed and observations were noted according to the following categories:
  - A. Written instructions or data sheets, do not address the discrepancy completely
  - B. Drawing requirements incorrectly incorporated, incorrect, or missing (e.g., welds, holes, etc.)
  - C. Other data specification incorrectly incorporated, incorrect, or missing (e.g., verification of detail revision of specifications were used)
  - D. Parent inaccuracies, incorrect, or missing
  - E. Data reported not within specified limits
  - F. Paper has open work order
  - G. Wrong steps included
  - H. Wrong method, process but not complete (i.e., incomplete second, but not all)
  - I. Incorrect requirements
  - J. Other

---

RCC Production

**RCC Paper Review Summary (continued)**

- Total of 186 observations made during review:
  - A majority of the observations were documentation issues only
  - Many issues have been corrected through previous improvements and would not recur today
  - Most of the observations would have an adverse effect on the final RCC parts
  - The observations made by the review team break down as follows:
    - Category A: 12 observations
    - Category B: 5 observations
    - Category C: 7 observations
    - Category D: 159 observations
    - Category E: 3 observations
  - These observations could affect product quality and must be addressed.

---

RCC Production

- Findings (agreed to by Curry, Gordon and Grant):
  - NDE technique and processes utilized at the supplier are out-dated
  - Low volume production work may result in poor quality
  - Senior personal at LM/MMF&CC have assessed the potential for NDE to inspect for substrate mass loss as improbable

- Recommendations (agreed to by Curry, Gordon and Grant):
  - Increase the fidelity and capability of NDE methods and equipment utilized during the production and refurbishment of RCC parts
  - Ensure NDE personnel training and skills
RCC Production

- Documentation:
RCC Mission Life Capability
RCC Mission Life

- **Action / Issue:** Determine adequacy of RCC mission life analysis methodology
- **Background / Facts:**
  - Oxidation rate is the most important parameter to determine mission life
  - Function of temperature, pressure and heating time
  - Resulting mass loss reduces part strength
  - Repeated exposure to the flight environment degrades the oxidation protection system and increases amount of mass loss
  - Mass loss rate characterized by laboratory testing

RCC Mission Life

- **Background / Facts:**
  - Arc jet test at Ames and JSC in 1973 first revealed mass loss with no apparent dimensional changes
  - Database generated for non-TEOS material
  - Arc jet and radiant exposure tests at JSC, ARC, LARC and Rocketwell
  - Established strength reduction as a function of mass loss
  - Mass loss greater in plasma arc jet (convective) than radiant tests
  - Mass loss correlation (radiant/convective) developed from the test results (see charts 7 and 8 for convective heating results)
  - Established need for improved coating system

RCC Mission Life

- **Background / Facts:**
  - TEOS infiltration system baselined for OV-102 in March 1978
  - Mass loss correlation for radiant and convective heating developed in 1978
  - Surface porosity effects on mission life discovered in December 1978
  - Type A sealant developed in 1980 to seal surface porosity
  - Retrofit onto OV-102 after 5th flight
  - Mass loss database developed in 1984
  - Double Type A (DTA) sealant developed to increase mission life
  - Baseline for OV-105 and all new parts
  - Mass loss database developed in 1994

RCC Mission Life

- **Convective Mass Loss Correlation**
- Rcorr/SIC/TEOS-Type A material system plasma arc jet tests for convective mass loss conducted at JSC in 1984
  - 40 total specimens, 2 each at 20 combinations of temperature and pressure
  - Temperature ranged from 1000 to 1000 F
  - Pressure ranged from 0.01 to 0.05 atmospheres
- Test results summary
  - SIC erosion occurred at temperatures at 2800 F and above
  - Specimens exposed to temperatures at 2700 F and below did not indicate a thickness change
  - Mass loss rates increase rapidly above 2500 F
  - See next 2 charts for actual results
RCC Mission Life

**Determination**

- **Background / Facts:**
  - Determination of mission lives due to operational aging includes both thermal and structural analysis results.
  - Thermal analysis determines mass loss based on certification mission profiles (closest match to each actual mission).
  - Structural analysis determines strength based on air loads and thermal loads.
  - Margin of safety is determined for longest possible mission life while preserving the required factor of safety = 1.4.

**Allowable Stress for Some Properties**

- **Background / Facts:**
  - OV-102 RCC components were not coated with Type A sealant for the first 5 missions – reduced mission lives from other orbiters.
  - RCC refurbishment intervals established to replenish Type A sealant to achieve desired mission life.
  - Minor repair capability developed to allow for continued operation between scheduled OMM downtime.
  - Minimum predicted life for WLE RCC component on OV-102 is 50 missions for panel/seal 9 assembly.
RCC Mission Life
Destructive Testing

- Background / Facts:
  - Destructive testing performed on OV-102 panel 12R (15 flights) and panel 10L (19 flights) to compare to design allowables
  - Documented in LMM&FC report 221RP10556, Sep 1996
  - Data is limited and significant scatter exists, however test results indicate trends worse than expected (see next charts)
    - Tension test results below allowable at 0.02 psf (not 0.03)
    - Load test results below allowable at 0.02 psf (not 0.1)
    - Opening corner moment below allowable at 0.01 psf (not 0.03)
  - Destructive testing planned for OV-103 panel 10L exposed to 30 flights

RCC Mission Life
Destructive Test Results

RCC Mission Life
Destructive Test Results

RCC Mission Life
Destructive Test Results

RCC Mission Life
Destructive Test Results
RCC Mission Life

Destructive Test Results

- Insufficient data exists to compare predicted mass loss and strength to actual mass loss and strength of flown hardware due to repeated exposure.
- However, results to date indicate need to accelerate additional destructive testing of flown hardware.
- Only 2 tests were performed to determine oxidation associated with craze cracks used to develop tactile evaluation method for coating adherence reduction due to oxidation along interface.
- Recent NASA GRC examination of OV-102 panel 12R has revealed coating and substrate anomalies that warrant further investigation.

Category: Potential Contributor

Recommendations (Agreed to by Curry):
- Develop a plan to conduct destructive testing of flown RCC components that addresses:
  - Extensive NDE to select test specimen locations.
  - Predicted mass loss rates and corresponding reduction in mechanical properties versus actual test results.
  - Type A sealant loss on OML.
  - Pinhole impact on coating adherence and mechanical property reductions.
  - Oxidation associated with craze cracks.
  - Substrate oxidation impact on mechanical properties.
  - Impact energy resistance due to launch/ascent debris.
- Conduct testing of flown hardware ASAP per above plan.

Documentation:
- NASA GRC Briefing by A. Calimino, "Microstructural Characterization of RCC Materials", 16 May 2003
RCC
Fleet Experience – Aging

8-1  RCC Maintenance Actions
8-2  Pinholes in RCC Components
8-3  Deterioration of Type A Sealant
8-4  NDE of RCC Components
WLE Maintenance Actions

- **Action/Issue:** WLE maintenance actions evaluated for negative trends of damage experience not already incorporated into new OMRSD requirements.
- **Background:**
  - 3 RCC panel/seals have been replaced on OV-102
  - Replaced panel/seal 12R after 15 flights for destructive testing
  - Replaced panel/seal 10L after 15 flights for destructive testing
  - Replaced panel/seal 11L after 15 flights due to fix-up issues with the new panel/seal 10L
  - Removed panel/seal 11L (P/N 10211LA001) is currently in the spares pool

RCC Maintenance Actions

- **Panel 8L (STS-103)**
  - Suspected Oxidation At SIC and Substrate Interface

- OV-102-26, T-Seal 11L Cavity (Dec 00)

- OV-103-29, Panel 10L Coating/Substrate Loss (Apr 01)
  - Suspected Oxidation At SIC and Substrate Interface

- OV-103-30, Panel 10L Repair (Aug 01)
  - Damaged After 1 Flight, Panel Scrapped
RCC Maintenance Actions

OV-102 Left WLE RCC Panel/T-Seal Maintenance

- Replaced
- Repaired
- Refurbished

OV-102 Right WLE RCC Panel/T-Seal Maintenance

- Replaced
- Repaired
- Refurbished

RCC Maintenance Actions

OV-102 Left WLE RCC Panels

- Replaced
- Repaired
- Refurbished

Panel/T-Seal Location

RCC Maintenance Actions

OV-102 Left WLE RCC T-Seals

- Replaced
- Repaired
- Refurbished

Panel/T-Seal Location

RCC Maintenance Actions

- Background / Facts:
  - WLE RCC T-Seals cracks discovered on OV-104, 1/7 during OMRED turnaround inspection in 1991
  - All WLE RCC components inspected - no cracks discovered in RCC panels
  - 20 of 132 T-Seals were cracked, all within 0.5 inches of apex
  - OV-102: 11 cracked T-Seals, crack lengths less than 0.5 inches
    - Determined to be normal shrinkage cracks, not visible with unaided eye, all reinstalled in OV-102
  - OV-103: 1 cracked T-Seals, crack lengths up to 2 inches, replaced with new spares
  - OV-104: 8 cracked T-Seals, crack lengths up to 2 inches, replaced with new spares

RCC Maintenance Actions

Typical RCC T-Seal Cracks (1991)
RCC Maintenance Actions

- Background / Facts:
  - RCC T-Seal Cracking investigation documented in Rockwell Report LTR 4068-2401, November 1991
  - Sectioned OV-104, 17R (worst cracking) and 18R (3rd worst case) for failure analysis
    - No substrate cracks
    - Laminates significantly distorted
    - OV-104 panel 17R had oxidation damage
  - Removed coating from several other T-seals – no substrate cracks found
  - Conclusions from failure analysis (metallographic, fractography, etc.)
    - Cracks only in SiC layer
    - Cracks due to variations in fabrication lay-up process resulting in different laminate distortions

RCC Maintenance Actions

- Background / Facts:
  - Determined full length SiC layer crack does not affect static strength
  - Analyzed full-length substrate crack
    - Factor of safety > 1.4 for entry landing
    - Factor of safety = 1.38 for ascent
  - Tested 2 T-seals for coating crack growth characteristics at a stress level of 80% of design limit in 1991
    - Tested OV-102 #9 left (between panels 9 and 10) for 400 cycles – determined via analysis and inspection negligible fatigue damage occurred and re-installed T-seal in OV-102
    - Tested OV-104 RH #18 for 100 cycles – no crack growth, part was scrapped for destructive testing

WLE Maintenance Actions

- Background / Facts:
  - OV-102 wing leading edge spars have a history of degradation due to corrosion
    - Design corrosion protection system was a single coat of MB0125-055 primer (Korpon)
    - MB0130-119 Type II RTV adhesive applied as a galvanic barrier on forward most plane of corrugated spar
    - Design change incorporated at J2 OMDP to apply 2 coats of Korpon and cover with RTV topcoat as moisture and galvanic barrier
  - Inspection process updated
    - Full inspection performed every 4 and ½ years (V39KG0.060 and V30L0G0.06) which requires removal of all RCC panels and associated support fittings and insulators
    - Sampling inspection performed every 3 years (V39KG0.065 and V30L0G0.065) for 6 panels per side

WLE Maintenance Actions

- Background / Facts:
  - OV-102 inspections performed in conjunction with WLE refurbishment per MCR18457 during J2 resulted in significant corrosion findings
    - 41 doubler required on the right side
    - Multiple doublers required on the left side
  - Exploratory holes were drilled for core inspection and no corrosion was detected
  - Inspections during J3 did not detect evidence of corrosion on the WLE spars
WLE Maintenance Actions

- **Findings (agreed to by Curry, Gordon and Grant):**
  - More unplanned maintenance actions on OV-102 left versus right wing RCC parts (varies with other vehicles)
  - A fatigue tested T-seal was installed in OV-102
    - Determined most likely not a contributor to the accident
    - However, the practice of utilizing fatigue tested components in a vehicle should be discontinued
- **Recommendations (agreed to by Curry, Gordon and Grant):**
  - Determine root cause for all exterior damage found and adjust maintenance requirements as needed

---

**Documentation:**
RCC Pinholes

Action / Issue: Determine adequacy of pinhole corrective actions

Background / Facts:
- Pinholes first discovered on OV-102 after 12 flights in 1992
- Pinholes subsequently found on all other orbiters
- Pinhole size/quantity increased with flight exposure
- Testing was performed to determine root cause of pinholes based on several theories
  - Zinc oxide contamination
  - Sea mist salt contamination
  - TECOS application

Typical Pinholes (1992) First Discovered on OV-102-12

Background / Facts:
- OV-102 RCC panel 12R removed after 15th flight for detailed destructive evaluation in October 1993
  - Reference Rockwell Report LTR 6322-4039, Dec 1994
- Optical and SEM evaluation performed on 15 pinholes
  - Majority of pin holes occur along craze cracks in SiC layer
  - Typically in thick regions of SiC layer - indicative of porous substrate
- Pinhole glass chemistry determined
  - Silicon, oxygen, aluminum and zinc
- Zinc not a part of the RCC material system – suggested contamination from external source
- 8 samples collected from the RSS of pad 39A in July 1994 and zinc was identified via chemical analysis

RCC Pinholes Cross-Section

OV-102 Panel 12R After 15th Flight

Mouth of a Pinhole, Magnification Approximately 130X
Actual Pinhole Diameter = 0.01 inches

RCC Pinholes

Background / Facts:
- Zinc oxide contamination determined to be root cause
  - Reference Boeing Report KLQ-98-005, Launch Pad Zinc Fallout Determination, 22 December 1996
  - Launch pad service structure protected with a two-coat primer and topcoat system
  - Primer contains metallic zinc dust in a silicate binder
  - Launch pad refurbishment process discontinued topcoat repairs
  - Weathering of exposed primer caused zinc oxide powdery residue
  - Rain washed the zinc oxide onto the orbiter
  - During reentry, zinc oxide reacts with the SiC layer resulting in pinholes and the zinc containing glass on the part surface

RCC Pinholes Surface View

RCC Pinholes
**RCC Pinholes**

- **Background / Facts:**
  - NASA review of old plasma jet test specimens indicated formation of small anomalies similar to pinholes but not typical of flight induced pinholes
  - Specimens with pinholes made from OV-102 panel 12R
    - Tested for 3.5 hours
    - Temperature ranged from 2400°F to 3000°F
    - Pressure ranged from 0.014 to 0.10 atmospheres
    - Testing did not significantly change pinhole dimensions nor substrate oxidation

---

**RCC Pinholes**

- **Background / Facts:**
  - Developed Type A sealant refurbishment process at Lockheed-Martin to repair pinholes
  - Process described in maintenance requirements portion of the briefing
  - Added step to fill pinholes with Type A sealant
  - Refurbishment does not prevent pinholes from reforming or restore carbon substrate integrity
  - Implemented refurbishment plan on all vehicles

---

**RCC Pinholes**

- **Background / Facts:**
  - Inspection acceptance criteria established
    - All pinhole-related glass formations are acceptable regardless of the localized surface roughness associated with the formation (paragraph 4.12.9.1)
    - Pinholes are acceptable during routine processing flows (paragraph 4.12.9.2)
    - Pinholes greater than 0.04 inches are unacceptable during OMM (paragraph 4.12.9.3)

---

**RCC Pinholes**

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*Highest values shown in red*
RCC Pinholes

Findings (agreed to by Curry):

- Refurbishment intervals and process established to repair pinholes, maintain sealant, and achieve maximum mission life
- Accept/reject criteria allows for pinholes greater than 0.04 inches in service provided the underlying substrate is not exposed
- 2003 launch pad zinc sampling indicates RSS is still a source for zinc contamination and potential pinhole formation

RCC Pinholes

Recommendations (agreed to by Curry):

- Consider taking action to minimize the potential of zinc contamination by judicious maintenance of the topcoat and/or protection of the RCC material system from rain water
- Determine the number and size of pinholes expected based on the current maintenance requirements and impact on structural integrity

RCC Pinholes

Documentation:

- ML0601-0002, "Reusable Surface Insulation Acceptance Criteria for Operation Vehicles", 19 September 2002

RCC Pinholes

Documentation:

- Rockwell briefing by M. Gordon, "RCC Pinhole & Sealant Loss Investigations at KSC", 11 September 1995
- Rockwell Report LTR 6322-4039, "Examination of RCC Pinholes", December 1984
- Rockwell briefing by G. Treadel, "Porosity of RCC Wing Edge Panels", 7 September 1993
RCC Type A Sealant

- **Action / Issue:** Deterioration of Type A sealant

- **Background / Facts:**
  - Discovered white residue on WLE RCC panels on OV-102, OV-104 and OV-105 in November 2001
  - Lab results determined deposits to be sodium carbonate
  - Root cause determined to be the Type A sealant converting to sodium carbonate when exposed to rain water

---

RCC Type A Sealant

- **Background / Facts:**
  - There are 3 possible outcomes for sodium carbonate deposits
    - Deposits are washed off and removed
    - Would decrease sealant effectiveness
  - Deposits remain on surface, melt on re-entry, and combine with glass
    - Favorable outcome, restores the composition of Type A sealant
  - Deposits remain on surface, melt on re-entry, and flow to other parts
    - Potentially damaging and needs to be monitored

---

RCC Type A Sealant

- **Findings (Agreed to by Curry):**
  - Root cause determined and found not to be detrimental to RCC
  - Deposits are potentially damaging to metallic hardware

- **Recommendations (Agreed to by Curry):**
  - Continue previous investigation of an improved sealant system
  - Continue monitoring for potential flow of deposits onto metallic hardware
RCC Type A Sealant

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RCC Type A Sealant

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  - Continue previous investigation of an improved sealant system
  - Continue monitoring for potential flow of deposits onto metallic hardware

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RCC Type A Sealant

- **Documentation:**
  - Briefing by N. Jacobson et al., "Chemistry of Sodium Carbonate Deposits on the Orbiter Wing Leading Edge and Nose Cap"
  - Briefing by D. Curry et al., "Orbiter Reinforced Carbon/Carbon Advanced Sealant Systems Screening Tests", January 2000
**RCC NDE**

- **Action / Issue:** Determine NDE requirements for RCC components
- **Purposes of NDI:**
  1. Verify no carbon substrate defects exist of a quantity and size distribution that could result in structural failure
  2. Verify no SiC/substrate interface defects exist of a quantity and size distribution that could result in loss of the SiC layer and expose the carbon substrate
  3. Validate the mass loss analysis methodologies and support determination of mission life capability for each RCC part

**RCC NDE**

- **Basis for Purpose 1 (Carbon Substrate):**
  - Visual and thermography NDE results of OV-104 panel 16R revealed surface and subsurface defect indications (see next chart)
  - X-Ray computed tomography NDI technique performed by Wyle Laboratories on same panel in Nov 02
    - 75 CT slices were obtained
    - Subsurface defect indications were confirmed (see next 4 charts)
**RCC NDE**

**Subsurface Indications**

**Surface Defects**

OV-104-24, Panel 16R CT Results (Nov 02)

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**RCC NDE**

- **Basis for Purpose 1 (Carbon Substrate) Continued:**
  - A study was performed on OV-103 and OV-105 RCC panels using thermography
    - Reference briefing by KSC personnel
    - Concentrated on panels 7 through 12, left and right
    - All 24 panels appeared to be in good condition
  - As an additional test, OV-103 panel 16R was inspected using thermography
    - Subsurface defect indications observed (see next chart)

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**RCC NDE**

0.234-0.651 Seconds (Averaged) 0.334-0.851 Seconds (Averaged)

OV-103-30, Panel 16R Thermography Results (Nov 02)

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**RCC NDE**

- **Basis for Purpose 2 (SIC Layer):**
  - 6 occurrences of SIC layer loss or damage have been identified
    - November 1997, OV-102-24 (STS-87), 3 damaged parts
      - Reference Boeing Report KLO-98-002, March 1998 (no photos included in report)
      - Panel 19R, 0.040" diameter, 0.035" deep exposing carbon substrate
      - Panel 17R, 0.1" x 0.2" x 0.025" deep exposing carbon substrate
      - Arrowhead, 0.2" x 0.15" x 0.020" deep exposing carbon substrate
    - January 2000, OV-103-27 (STS-103), Panel 8L, panel scrapped
    - December 2000, OV-102-26 (STS-93), T-Seat 11L
    - April 2001, OV-103-29 (STS-102), Panel 10L

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**RCC NDE**

Panel 8L (STS-103)

Suspected Oxidation At SIC and Substrate Interface

OV-103-27, Panel 8L, SIC Loss (Jan 00), Panel Scrapped

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**RCC NDE**

OV-102-26, T-Seat 11L, SIC Damage (Dec 00)
RCC NDE

• Basis for Purpose 2 (SiC Layer) Continued:
  - Pinholes in SiC layer have potential to result in oxidation of the carbon substrate and/or SiC/substrate interface
  - Majority of pinholes occur along craze cracks in SiC layer
  - Typically in thick regions of SiC layer — indicative of porous substrate
  - Oxidation below the SiC layer has been discovered associated with pinhole locations (see next chart)

OV-102 Panel 12R After 15th Flight

RCC NDE

• Basis for Purpose 3 (Mission Life):
  - Destructive testing performed on OV-102 panel 12R (15 flights) and panel 10L (19 flights) to compare to design allowables
    • Documented in LMM&FC report 221R010598, Sep 1996
  - Data is limited and significant scatter exists, however test results indicate trends worse than expected (see next charts)
    • Tension test results below allowable at 0.02 psf (not 0.03)
    • Lug test results below allowable at 0.02 psf (not 0.1)
    • Opening corner moment below allowable at 0.01 psf (not 0.03)
  - Results indicate mass loss prediction method should be revalidated

RCC Tension Test Results
OV-102 Panel Compared to Design Allowables

Silicon Carbide Layer
(0.02" to 0.04")

Subsurface Oxidation

(2" x 0.37" x 0.018")

OV-103-29, Panel 10L SiC Loss (Apr 01)
RCC NDE

• Basis for Purpose 3 (Mission Life) Continued:
  – X-ray Computed Tomography (CT) NDI technique demonstrated to be viable for determining variable RCC mass loss due to oxidation

RCC NDE

• Findings (agreed to by Curry, Gordon and Grant):
  – Damage and defects discovered on RCC components warrants development of NDI techniques to verify structural integrity
  – Recommendations (agreed to by Curry, Gordon and Grant):
    – NDE all flown WLE RCC parts ASAP to support investigation
    – Determine defect quantity and size distribution
    – Use results to determine what parts should be included in the impact test program
    – Identify and implement NDE techniques for carbon substrate and SC/substrate layer inspection as a return to flight criteria and for routine use
    – Develop and implement NDE techniques for carbon substrate mass loss to validate analysis methods and results (need date is TBD)

RCC NDE

• Recommendations Continued (agreed to by Curry, Gordon and Grant):
  – NDE technique development and application should address the following
    • NDE standards
    • Probability of detection
    • Inspector certification requirements
    • Basis for accept/reject criteria
    • Basis for inspection frequency
    • How NDE results will be used in the mission life analysis
    • If production NDE techniques and processes are used, demonstrate the adequacy to include detection capability, accept/reject criteria, and implications to structural integrity via mechanical testing as was performed originally
RCC NDE

• Documentation:
  - Wyola Laboratories Report, "CT Inspection of OV-104 RCC Panel", P. Engel, 22 November 2002
RCC Maintenance

9-1 RCC Maintenance Requirements
9-2 RCC Maintenance Repair and Refurbishment Process
9-3 Left WLE Maintenance During OMM & Flows
9-4 LESS Hardware Use
RCC Maintenance Requirements

- **Action / Issue:** Determine adequacy of RCC maintenance requirements
- **Background / Facts:**
  - RCC inspection requirements are documented in NSTS 08171, OMRSDF File III, Volume 9 and Volume 30
  - Inspection methods are primarily visual
  - Tactile pressure test of large craze cracks performed to identify excessive subsurface oxidation
  - Accept/reject criteria established for expected defect types and locations

RCC Maintenance Requirements

- **Background / Facts:**
  - RCC tactile pressure requirements are documented in NSTS 08171, OMRSDF File III, Volume 9, Number V00A00.075
  - Use compressive gloved-finger technique only at the inboard and outboard regions adjacent to each T-seal of each panel
  - Region limited to within 12 inches of panel apex
  - Panels 6 through 17 are inspected as a minimum
  - Additional panels may require tactile inspection based on craze crack sizes

RCC Maintenance Requirements

- **Findings (agreed to by Curry, Gordon and Grant):**
  - Established maintenance requirements are thoroughly documented
  - No NDE technique is routinely employed during maintenance of RCC
  - Inspection requirements and accept/reject criteria appear to be difficult to implement consistently
  - Protection of RCC during maintenance is inadequate against tool drops, impact from maintenance stands, etc.
- **Recommendations (agreed to by Curry, Gordon and Grant):**
  - Improve the protection of RCC components in the maintenance facilities
  - Reevaluate adequacy of maintenance requirements considering inspection burden and reliability of visual method

RCC Maintenance Requirements

- **Documentation:**
  - ML0901-0002, "Reusable Surface Insulation Acceptance Criteria for Operational Vehicles", 19 September 2002
RCC Repair & Refurbishment

- Action / Issues: Determine adequacy of RCC repair and refurbishment requirements
- Repair Process:
  - Repairs are performed using Boeing Specification ML0601-9026, Procedure TP8-365, RCC Coating Repair
  - Repairs to RCC parts limited to minor damage to Silicon-Carbide coating
    - Repairs are performed at KSC
    - Not authorized for pinholes and substrate damage
  - RCC repair involves the following process steps:
    - Part cleaning
    - Type A sealant application
    - Sanding of repaired region to meet flushness requirements

RCC Repair & Refurbishment

- Refurbishment Process:
  - Refurbishments are performed using Lockheed-Martin Specification 506-RCC-318, Refurbishment of Flown RCC Parts, 16 February 2000
  - Refurbishments to RCC parts performed to achieve the desired part mission life by replenishing the Type A sealant
  - Refurbishments performed by only Lockheed-Martin using the following process:
    - Type A sealant removed by sanding
    - Vacuum heat clean to bake-out contaminants
    - Pinholes repaired using Type A sealant forcefully wiped into the holes
    - TEOS impregnation and cure
    - Type A sealant application and cure
    - Reassembly of the metallic parts to the RCC panel

RCC Repair & Refurbishment

- Background / Facts:
  - Refurbishment interval established based on destructive evaluation of OV-102 panel 12R after 15th flight
    - Reference Rockwell Report LTR 6322-4039, "Examination of RCC Pinholes", December 1994
    - Evaluation performed to characterize pinholes
    - Discovered that CML is losing the Type A sealant layer
    - Type A sealant thickness measured near 5 pinholes
      - Minimum ranged from 0.0001 to 0.0002 inches
      - Maximum ranged from 0.0006 to 0.0014 inches

RCC Repair & Refurbishment

- OV-102 Panel 12R After 15th Flight
  - Pinhole Cross-Section, Magnification Approximately 200X

RCC Repair & Refurbishment

- OV-102 Panel 12R Type A Sealant Thickness After 15 Flights

Pinhole Specimen Number (5 Pinhole Regions Examined):
RCC Repair & Refurbishment

- **Background / Facts:**
  - Since significant substrate oxidation was not found with panel 12R, established refurbishment interval to be every other OMM
  - Approach was supported by arc-jet testing in the mid-1990s
  - Refurbishment intervals are documented in OMM File II, Volume 3
    - 18 missions for panel/T-seal assemblies 6 through 17
    - 36 missions for panel/T-seal assemblies 18 and 19
    - Implies no refurbishment is required for panel/T-seals 1 through 5 and 20 through 22

RCC Repair & Refurbishment

- **Findings (agreed to by Curry):**
  - Refurbishment of panel/T-seal assemblies 1 through 5 and 20 through 22 are not required

- **Recommendations (agreed to by Curry, Gordon and Grant):**
  - Conduct evaluation of RCC panels to determine Type A sealant thickness loss rate at various locations as part of the planned destructive testing of RCC panels
  - Use above result to confirm or revise current refurbishment intervals

RCC Repair & Refurbishment

- **Documentation:**
  - Lockheed Martin Letter 3-47203/2L-129, "RCC Coating Repair History", 16 May 2002
  - Vought Letter 3-47700/5L-1276, "Refurbishment of OV-102", 1 November 1995
**RCC Maintenance OMM in 2000**

- **Action / Issue:** Determine potential for left WLE maintenance actions to be a contributing cause of the accident.

- **Background / Facts:**
  - OV-102 inducted into OMM after STS-93, 26th fight for OV-102.
  - OMM conducted at Palmdale October 1999 through February 2001.
  - All WLE RCC components were removed to accomplish required inspections.
  - RCC panel T-seals 6, and 13-17 were refurnished.
  - RCC parts were inspected for pinholes, etc.
    - Pinholes in Panel 8 and 19 originally reported > 0.04 inches in diameter (TES-2-J3-0412, 0416).
    - Quality evaluated pinholes using optical comparator and determined them to be within acceptable limits.

---

**RCC Maintenance OMM in 2000**

- **Background / Facts:**
  - After re-installation of the RCC components, step and gap measurements were found to be unacceptable (TES-2-J3-0495).
  - Complete removal of Left WLE subsystem was performed and the following issues were discovered:
    - Spar fitting shims not per design (STR-2-J3-0703).
    - Lower access panel nutplate issues (TAR-2-J3-0689).
    - Debonded nutplates, low running torque and damaged nuts (TES-2-J3-0439).
  - Evaluated 152 of the 176 fitting fasteners (24 were not evaluated since some fittings were already removed):
    - 104 of 152 (68%) were per drawing requirements.
    - 48 of 152 (32%) had low torque values.

---

**RCC Maintenance OMM in 2000**

**OV-102 Fastener Detail**

Design Configurations:
- Bonded Alum Plate RIVeted-REPLATE
- MR Riveted Config.
- Washer and Nut No Thread Relief

**RCC Maintenance OMM in 2000**

**OV-102 Left Wing Torque Check Results**

- Tight: Left and Right Bolt Torque
- Bolt torque below 175 lbf•in (below 20% of max torque) is not acceptable.
- Bolt torque below 157 lbf•in is not acceptable.

---

**RCC Maintenance OMM in 2000**

- **Background / Facts:**
  - Improper shims resulted in small-out condition in some locations.
  - Observed in MR nut and washer rework areas only.
  - Shim stack returned to original build configuration.
  - Bolt torque sequence standardized to reduce panel tension and deformation.
  - Sequence steps and torque increments defined.
  - Torque checked after a minimum of 24 hours.
  - Both OV-102 wings reworked to design configuration.
  - Boeing Specification ML9301-0023 installation procedures revised.

---

**RCC Maintenance OMM in 2000**

**OV-102 Left Wing Fastener Shank-Out Check Results**

- Total % of Total:
  - Right - Design Configuration with No Shank-Out: 163/200 (82%)
  - Right - Design Configuration with Shank-Out: 5/200 (2.5%)
  - Left - Design Configuration with Shank-Out: 20/200 (10%)
  - Left - Design Configuration with Shank-Out: 20/200 (10%)
**RCC Maintenance**

**2. WLE Attach Fitting Bolt Torque**

- **RCA**
  - Breakage of the fitting bolt
  - Breakage of the O-ring seal
  - Stress relief of the fitting bolt
  - Breaking of the bolt and the fitting bolt

**Finding**

- **RCA**
  - Breakage of the fitting bolt
  - Breakage of the O-ring seal
  - Stress relief of the fitting bolt
  - Breaking of the bolt and the fitting bolt

**Procedure**

- **RCA**
  - Breakage of the fitting bolt
  - Breakage of the O-ring seal
  - Stress relief of the fitting bolt
  - Breaking of the bolt and the fitting bolt

**OV-102**

- **RCA**
  - Breakage of the fitting bolt
  - Breakage of the O-ring seal
  - Stress relief of the fitting bolt
  - Breaking of the bolt and the fitting bolt

**OV-102**

- **RCA**
  - Breakage of the fitting bolt
  - Breakage of the O-ring seal
  - Stress relief of the fitting bolt
  - Breaking of the bolt and the fitting bolt

---

**RCC Maintenance**

**After STS-109**

- **Background / Facts**:
  - STS-109, 27th flight for OV-102 launched 1 March 2002
  - Post-flight processing performed May 2001 through Jan 2002
  - Upper wing discoloration discovered near panel 15 left
  - Upper and lower access panels removed for inspection
  - Baseball size hard object found
    - Most likely glass-backed white masking tape
    - Tape used for paint masking may have fallen into RCC cavity during OM&M
  - Area cleaned and accepted with MR concurrence

---

**RCC Maintenance**

**Before STS-107**

- **Background / Facts**:
  - Pre-flight processing performed Mar 2002 through Aug 2002
  - STS-107, 28th flight for OV-102 launched 16 January 2003
  - OV-102 left wing horsehoe gap fillers were removed and replaced at panels 1, 19 and 20
  - Gap filler repaired during OM&M J3 and found torn following STS-109

---

**RCC Maintenance**

**OMM & Flows**

- **Findings (agreed to by Curry, Gordon and Grant)**:
  - Significant WLE maintenance performed during OM&M J3
  - Few maintenance actions after OM&M J3 and prior to STS-107
  - Not all the fittings on OV-104 are scheduled for bolt torque prior to next flight

- **Recommendations (agreed to by Curry, Gordon and Grant)**:
  - Perform torque of OV-104 attach fitting bolts prior to next flight
RCC Maintenance
OMM & Flows

- Documentation:
  - Briefing by E. Statham, "Palmdale Processing Review Team Status Briefing", 25 February 2003
**RCC Maintenance**

**Maintenance Practices: LESS Hardware Use**

- **Action / Issue:** Review/assess orbit Leading Edge Structural Subsystem (LESS) maintenance practices regarding hardware use

- **Background:**
  - LESS consists of:
    - 22 Reinforced Carbon-Carbon (RCC) panels on each wing
    - 44 carrier panels: 22 upper, 22 lower on each wing
    - Numerous other components (spar insulators, clevis insulators, spinner head insulation, attach fittings, brackets) and hardware (bolts, pins, sleeves, etc)
  - LESS subjected to thermal and aero stresses during reentry
  - Proper inspection/maintenance of components essential to system performing as designed/intended

- **Findings:**
  - Work Authorization Documents (WADs) vary specific on most tasks
  - One exception: carrier panel (C/P) hardware (A286 bolt) reuse
    - 4 bolts per upper panel, 2 per lower panel
    - Engineers initially stated bolts are reused
    - Technicians stated hardware is discarded/replaced
    - Inspected multiple storage containers holding removed C/Ps
      - No bolts found
    - After further discussion, engineers restated bolts "can be reused" at technician's discretion, based on cleaning (using isopropyl alcohol) and visual inspection

- **Findings (cont'd):**
  - Unlike the predominance of WADs reviewed, the C/P WADs provide no clear guidance on hardware disposition
    - Both WADs (removal and installation of C/Ps) reviewed
    - No specific requirement to clean, inspect, or reuse (or replace)
    - By contrast, WADs covering removal of RCC panels clearly state “…identify, bag and retain hardware for future use” with respect to four separate component removals
    - Verified through physical inspection of removed components
    - Inconsistent/balking guidance allows varying interpretations and creates the potential for process variation(s)

- **Findings (cont'd):**
  - Results of investigation by metallurgist
    - "There was no evidence of stress corrosion cracking at pre-launch conditions. There was no evidence of cumulative failures that started on previous missions."
  - **Recommendations:**
    - Eliminate the potential for varying interpretations of carrier panel bolt reuse by making the WADs more specific
Tile
Design – Certification

10-1 Design for Impact Resistance
STEPS-27R, OV-104, Flight 3

Robert "Hoot" Gibson

Composite of Post-Flight Damage

2500 Tile

2500 Tile

1000 Tile

1000 Tile

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Tile Design – Certification

• Findings (cont’d):
  - The loss of a single tile before entry interface on the lower surface of the orbiter forward of location X,1367 could result in the loss of the orbiter. The loss of two tiles before entry interface on the lower surface of the orbiter forward of location X,1367 would most likely result in the loss of the orbiter [67].
  - Some tiles possess more risk than others: some tiles have a greater probability of being struck by debris, some locations are subject to greater heat load, and some locations have are adjacent to critical non-structural components [72].
  - The orbiter has been subjected to debris strikes since its first flight. Yet the requirements to tolerate or resist debris impact are exceedingly weak for general impact resistance and nonexistent for debris impact during launch [17].

Tile Design – Certification

• Recommendations:
  - Compute/analyze the distribution of known damage sizes and locations
  - Establish the critical damage size for each critical location
  - Identify the consequences of sustaining critical damage in a critical location
  - Compute the probability of sustaining critical damage in a critical location based upon a predictive model that accounts for impacts of debris emanating from various sources
  - Develop a tile designed to withstand the critical damage computed for various locations and install it at those critical locations

References
Tile
Fleet Experience – Aging

11-1  Tile System Integrity
11-2  Lost Tiles
11-3  Lack of NDI/E
11-4  Potential for Corrosion
11-6  Tile Shrinkage
Tile System Integrity

- **Action / Issue:**
  - Tile system components may degrade as a function of thermal/mechanical loads, chemical environment, and calendar time.

- **Tile System Components:**
  - Reaction layered glass (RLG) coating
  - U-005 to Tile Gap
  - Tile extruded layer
  - RYT adhesive
  - Keropon primer
  - Keropon interlaminated structure

- **Strength Test:**

What will be the Weak Link In the Future?

- **Evaluate each tile component for aging effects:**

  - Strength Test:
    - The question: Do these properties change as a function of thermal/mechanical loading, ground environment and/or time?

Coating/Tile/Densification Integrity

- **Background / Facts:**
  - Tile "poisoning" possible and inhibits efficacy of re-wetting/reproofing; however, treatment of tile with multiple injection of DNEP overcomes "poisoning."
  - Cooper test was used to evaluate mechanical strength under various loads.

- **Findings:**
  - Evaluation of coating, substrate and densification to date indicates that tile should continue to be resistant to thermal/mechanical effects.

RTV Integrity

- **Background / Facts (cont'd):**
  - RTV Adhesive/Heat/sink/Screw
    - Adhesive, heat/sink, and screw are all RTV silicone products supplied by General Electric.
    - RTV known to degrade when exposed to certain environments.
    - HMDS waterproofing used on OV-102 and OV-103; degrades RTV strength properties.
    - A NASA/USA program is in place to sample and analyze RTV for degradation.

RTV Screed/Heatsink for OV-102

- **Background / Facts (cont'd):**
  - Red indicates original installation of OML screed/heat sink [63]
  - Tiles over OML screed/heat sink subjected to HMDS.

Major Factors For RTV Degradation Have Been Identified

- **Risk Mitigation:**
  - Degradation from radiation damage and high temperature exposure.

  - No age-related mechanical failures have been identified.
  - Sampling program has not shown signs of degradation over time.

  - Thermal exposure to 300°F for 1 hour exposure to 375°F.
  - Densification temperature of 1 hour exposure to 375°F.

  - No age-related mechanical failures have been identified.
  - Sampling program has not shown signs of degradation over time.

  - Stress and damage due to thermal expansion differential of structure and RTV.
  - Accelerated testing: high temperature, high stress, high pressure.
  - Accelerated testing: 480°F, 480°F, 480°F exposure over time.

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RTV Bondline Sampling Test Program (Since 1980s) [30]

- Samples are taken from key areas of Orbiter per OMRSO 20A00
  - Hydrazine Fluid inspection - piano hinge body flap
  - Screw/Heatink inspection - 7 locations (from 14 options)
  - Orbiter RTV Bondline Sampling - 10 locations
- OM3 RTV Bondline Sampling - 1 sample per panel
- Samples accompanied by Tile Removal PR
  - Includes subjective evaluation of peel strength, tackiness
- Samples sent to Boeing H3 lab for analysis
- Derived Sear A Harness
- Gas Chromatography/Mass Spectrometry (GCMS)

Analysis Results Presented at 140 Process Review Board Every 2 Years Do Not Show Degradation Trends

Thermal Effects on RTV

- Background / Facts (cont'd):
  - Maximum structural surface temperatures experienced by OV-102 [82]
    - At 250°F, RTV/Corrosion average strength drops to 220 psi; material allowable drops to 120 psi at 350°F, allowable drops to <20 psi

Strain Isolation Pad (SIP) Integrity

- Background / Facts (cont'd):
  - Strain Isolation Pad (SIP)
    - SIP is a Nomex felt comprised of polyamide filaments formed into a pad
      - The felt is heat set at 500°F for 30 minutes to provide dimensional stability and then coated with RTV (0.006-0.010")
    - Multiple thicknesses are used:
      - 0.060-in for high modulus applications (e.g., near thermal barriers around doors)
      - 0.160-in for most applications (accretion tile)
    - Due to buy-out of SIP in the 1980's SIP is no longer manufactured
    - There is no structural requirement for SIP

SIP Integrity

- Background / Facts (cont'd):
  - Material allowances development [77]
    - Permanent extension of SIP (flatwise) occurs after exposure to cyclic mechanical loads
    - Testing to develop modulus included exposure of SIP (flatwise) to cyclic mechanical loads
    - Tensile strength (flatwise) specimens exposed up to 25 hrs at test temperature prior to test to failure

SIP Integrity

- Background / Facts (cont'd):
  - SIP properties are tested indirectly:
    - Indirect testing provides information about "threshold" strength, but cannot be used to model degradation effects
      - "Time aged" SIP tested indirectly during recertification of tile:
        - Tile densification qualification using a new coloring agent
        - AE1 tile certification for use on base heat shield
      - "Thermalmechanical" aging indirectly tested for 26 missions during certification of DXE3 rewaterproofing
      - "Thermalmechanical" aging indirectly tested during certification of AE1 tile system for 100 Orbiter missions
SIP Integrity

- Findings:
  - SIP currently thought to be robust
- Recommendations:
  - Direct testing and evaluation of SIP to assess aging effects is not necessary
  - Establish periodic testing of SIP stock to monitor potential aging effects due to time and, currently unknown, degradation effects

Koropon Primer Integrity

- Background / Facts (cont'd):
  - Super Koropon used as a primer on aluminum surfaces of orbiter
  - Over-spray of Koropon results in reduction in cohesion properties
  - Over-spray occurred during orbiter assembly and has occurred during insulation installation
  - Strength of RTV applied over bare aluminum greater versus application over Koropon
  - At 120°F the flatwise strength ("A") allowable of RTV over Koropon and RTV over bare aluminum begins to diverge; the allowable for RTV over Koropon drops to 13 psi at 350°F

Overall Findings and Recommendations

- Findings:
  - Effect of age and operational exposure not completely understood
    - Subnormal life component properties probably exist
    - Magnitude of degradation is unknown
  - The loss of two tiles before entry interface on the lower surface of the orbiter forward of X011357 would most likely result in the loss of the orbiter (1)
- Recommendation
  - Implement a program to systematically characterize effect of aging on all life system components relative to design conditions
    - Initial emphasis should be on Super Koropon and RTV

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**Tile Fleet Experience**

- **Action / Issue:**
  - It is not possible to determine when the tile system has degraded to the point where there will be a loss of tile.
- **Background / Facts:**
  - The loss of two tiles before entry interface on the lower surface of the orbiter forward of X/1587 would most likely result in the loss of the orbiter.
  - Many tile losses resulted in a design modification or change in process.
  - Did not know that something was wrong prior to flight.
  - Development and certification testing/analysis did not predict failure.
  - On average, tile is lost every 2 years (11 flights).
  - Last loss occurred 3 years ago (16 flights).

---

**Lost Tiles – All Orbiters**

- STS-41G
  - OV-99, Flight #6
  - 5 October 1984
  - Screw remained in cavity; initiated “Soft Screw” hunt.
  - Ultimately, 4011 tiles would be replaced.

**Right Wing Lost Tile**

- STS-51D
  - OV-103, Flight #4
  - 12 April 1985
  - Severe TPS damage on left outboard-elevator caused center panel burn-through and significant structural damage to the forward outboard corner of the elevator.

**Left Elevon Burn Through**

- STS-51D
  - OV-103, Flight #4
  - 12 April 1985
  - Severe TPS damage on left outboard-elevator caused center panel burn-through and significant structural damage to the forward outboard corner of the elevator.

**Lost Upper Body Flap Leading Edge Tile**

- STS-51D
  - OV-105, Flight #10
  - 11 January 1996
  - Bonded SIP and tile densification layer remained in cavity.

**Missing Chine Tile**

- STS-51D
  - OV-104, Flight #3
  - 2 December 1988
  - Cause: SRB Nose-cap Ablative Debris Strike

**Cause:** Inadvertent ground damage.
Lost Inboard Elevon Drain Tile

STS-103
OV-103, Flight #27
19 December 1999

Cause: Subnominal bond; incorrect filler bar contributed; difficult to read drawing (HT3, HT6)

Design / Mods / Manufacturing
TPS Under Wing

Findings:
- Cannot predict tile failure
  - Failure due to design, maintenance process changes and inadvertent ground damage
  - Effect of aging difficult to predict and may be a risk contributor in the future

Recommendations:
- The fact that a dominant or common cause does not exist underscores the need to address tile system integrity on several fronts: design and process change certification, training for maintenance personnel, clear process instructions, design of processes to reduce sensitivity and variance and NIHE or "health monitoring" system to aid in determining when tiles are damaged.
- Continue RIV sampling program to help assure ability to detect potential, and currently unknown, aging effects on tile system integrity.

References

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Tile Fleet Experience – Aging

- **Action / Issue:**
  - Bond-line integrity and/or strength is unknown
- **Background / Facts:**
  - Bond-line integrity
  - There are two techniques used to characterize bond-line integrity: a proof test (bond verification test) and the manual deflection test ("wiggle" test).
  - Bond verification (BV), for regular tile, is performed by attaching a specialized tensile test unit over the tile and utilizing a vacuum chuck tool. The maximum applied load is generally determined by using the known bond surface area multiplied by the stress levels given in the specification. The load is held at the maximum value for at least one second. For a typical lower surface regular five-inch square SIP footprint, the test load required to achieve the required 10-psf would be 250-lbs.

Maintenance Turnaround Work

- **Background / Facts (cont'd):**
  - A partial bond could exist and the BV test would not detect it.
  - There are specialized test load procedures for modified regular tile, irregular tile, structurally limited tile, tile bonded to filler bar, carrier panel tile, closeout tile and TUF-I-coated and TUF-I-RGC-coated tile.
  - Structurally limited tiles will be tested using reduced loads due to the structural limitations of the underlying substrate.
  - The tile bond is characterized as acceptable if the required tension load is sustained for one second without the tile pull-off.
  - Another method used to evaluate the tile to substrate bond is through the manual deflection test, also known as the "wiggle" test. This test requires an experienced technician to "wiggle" the tile and sense when the tile to substrate bond is unacceptable.

Current Method: Tile Bond Verification

**Chart:**

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Tile BV Compared to DLS

- **Background / Facts (cont'd):**
  - BV occurs when tile replaced.
  - 44% of tiles replaced prior to first flight (1981)

Heavy Reliance on Process Control and Sampling

- **Background / Facts (cont'd):**
  - There is a heavy reliance on process control to ensure tile system integrity.
  - Sampling program removes tile and samples RTV
  - Samples sent to Boeing HB labs for analysis
  - Derived Shore A Harness
  - Gas Chromatography/Mass Spectrometry (GC/MS)

Matrix of NDI/E Methods Evaluated Over the Years

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NDI/E Development and Evaluation

- **Background / Facts (cont'd):**
  - Boeing (Huntington Beach) is not in the business of developing tile bond-line NDI
  - Now allows NASA vendors to test NDI/E on specially fabricated test panels [14]

General Results of NDE/I Methods[10]

- **Background / Facts (cont'd):**
  - Changes in material properties, Tile (Silica & Al), SIP (Nomex), RTV thickness, Gap fillers (Fabric and Aluminum structure limit accuracy / repeatability of NDE to detect disbonds
  - None of the methods or combination of them could accurately detect disbonds
    - Suspect NDE disbonds were removed and evaluated as a good bond
    - NDE method would show promise when used on disbonds test panel but fail when tested on the Orbiter
  - New Tile disbond panel has been made and sent to NASA Marshall Space Flight Center for evaluation

Boeing Proposed New NDI/E Methods for Tiles

- **Background / Facts (cont'd):**
  - The following new NDE methods for detecting tile disbonds have been proposed[11]
    - Microwave Technology
      - Proposed by University of Missouri
      - Never funded or tested on TPS materials
    - Nonlinear Structural Dynamic Response
      - Proposed by Georgia Tech
      - Never funded or tested on TPS materials
    - Laser Vibration
      - Proposed by University of Central Florida
        - Funded by NASA KSC
        - Has been tested on Tiles

Lack of Tile NDI/E

- **Findings:**
  - There are no widely accepted NDE/I methods that are used to detect disbonds. General methods to detect a disbonds are in development, and the time when they will be available is unknown.
  - An even more useful NDI/E method would be one that can measure the bond strength. This is an even more challenging problem and will not likely be resolved in the near future.
  - The loss of two tiles before entry interface on the lower surface of the orbiter forward of X01357 would most likely result in the loss of the orbiter[11]
  - NASA and Boeing seem to have a sense for the need to develop a method to better quantify the bond-line integrity and have tested various methods on test panels and the orbiters

- **Recommendations:**
  - It is recommended that efforts to develop and evaluate NDI/E methods to assess bond integrity be given increased emphasis

References

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Tile
Fleet Experience – Aging

- Action / Issue: Current practice allows RTV adhesive over bare aluminum when bonding tile
- Background / Facts:
  - Process to remove and replace tile sometimes results in primer damage
- Findings:
  - NASA has current waiver to use heavily chromated primer, a proven corrosion control component, but currently recommends the removal of all damaged primer, leaving bare aluminum, prior to the application of a tile; this process was certified using results of extensive testing
  - Only one case of known corrosion according to NASA/USA personnel
    - Corrosion found on dome heat shield; edge exposed to environment
  - Active corrosion has never been detected on "acreage" tile
- Recommendations:
  - Initiate effort to determine long-term effect of practice
Tile
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  - Process to remove and replace tile sometimes results in primer damage.
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  - Only one case of known corrosion according to NASA/USA personnel.
  - Corrosion found on dome heat shield, edge exposed to environment.
  - Active corrosion has never been detected on “acreage” tile.
- **Recommendations:**
  - Initiate effort to determine long-term effect of practice.
Tile Shrinkage

- Action / Issue: Investigate orbiter flight problems related to tile shrinkage
- Background / Facts:
  - Tile shrinkage does occur during manufacturing
  - Localized heating results in tile repair and replacement
    - Localized high heating in flight causes tiles to shrink back, corners to round off, overhangs to slump, and tile to tile gaps to widen
    - STS-91 resulted in 8 tile replacements due to slumping on reentry
  - ISS missions have more severe reentry heating

Replacement of Complex Shaped Tiles is Expensive

- Findings:
  - Tile shrinkage generally not a safety-of-flight issue; it is a maintenance issue
  - Tile certification test indicate total gap sizes from 0.075-0.093 inches after a 100 mission simulation
    - Allowable gaps on the order of 0.025-0.056 inches, fill gap range from approximately 0.086-0.095 inches
    - Tile shrinkage of BRI-8 much less than LI-900

- Recommendations:
  - Revisit tile shrinkage as a function of temperature for acreage installations and assess long-term impact. If the ultimate solution to tile shrinkage is tile replacement at some time in the orbiter's life, it may provide further impetus to migrate to a tougher tile system

Areas That Typically Experience Slumping (Localized Shrinkage)

Complex Shaped Tiles

- Tile in Dam Area
- Elevon Hinge Ties
- Nose Landing Gear Door Tie
- Elevon Hinge Ties

Maximum Recorded OML Surface Temperatures

Temperatures Range from 1600F-2300F

Tile Shrinkage

- Background / Facts (cont'd):
  - Tile certification test results and temperature exposure profile

- For these tests, and tile exposed to high temperature
  - Orbiter tile not exposed on all sides during mission
  - These tests used to compare tile shrinkage of different tile materials

Dimensional stability of BRI-8, LI-900, and AETB-8

- LI-900: AETB-8: BRI-8
Tile Maintenance

12-1 Tile Repair Discrepancies
COLUMBIA
ACCIDENT INVESTIGATION BOARD

REPORT VOLUME V OCTOBER 2003

Tile Maintenance

- Action / Issue:
  - Some repairs performed on tile were not consistent with standard procedures.

- Background / Facts:
  - USA and NASA personnel reviewed 137 lower surface TPS WADs to determine in search of discrepancies that could have contributed to OV-102 failure.

- Findings:
  - Four of five tile repairs on the orbiter chine and lower surface were found to exceed TPS-211 repair criteria for maximum volume/depth.
  - One repair around the LMG door was found to be outside repair criteria found TPS-211 due to the failure to remove an existing repair prior to rework.
  - NASA reported the discrepancies did not present a safety-of-flight issue.

Example: Paper Study Find #105

Damage volume exceeds TPS-211 repair criteria, Volume exceeds limits. Previous repair should have been included in volume calculation [H22].

References

<table>
<thead>
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<th>Ref</th>
<th>Tab Number</th>
<th>Content</th>
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</table>

ST5-107 LH Wing TPS Process Review

"Findings of Concern" [H22]

- Findings:
  - WADs reviewed for LH Wing Lower Surface
  - 71 Matrix DRA (Not TIPS Tracked) were reviewed but are not included on the maps (minor putty repairs TPS-211/311)

Tile Maintenance

- Recommendations:
  - Determine cause of process escapes
    - Training, process clarity, etc.
  - Establish and execute action plan to mitigate the cause of process escapes

See also: Orbiter Maintenance (14-3)
Orbiter Design / Certification

28-1 Orbiter Design Concerns
Orbiter Design Concerns

- **Action/Issue:**
  - Unexplained Anomaly (UA) team has uncovered additional orbiter design and maintenance concerns that should be addressed.

- **Background:**
  - UA Team objective was to develop the effort required for safe Return to Flight utilizing UA logic and rationale.
  - UA Team reviewed all closure of areas that might warrant further action.
  - UA Team also addressed the vulnerability of critical lower surface areas which, while not a contributor to the accident, had potential for a critical breach and warranted design review action before relight.
  - UA charts for issues not addressed in other locations of the Matrix follow.

---

7. Door Seal Requirements

- **Japanese Text:**

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7. Door Seal Requirements (contd.)

- **Japanese Text:**

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8. Carrier Panel Bonded Studs

- **Japanese Text:**

---
Orbiter Design Concerns

5. Elevon Cove Carrier Panel Fasteners

**Remark:**

- 10-11-15: Revised 8-12-03.
- 8-12-03: Original Document.

**Description:**
The design of the elevon cove carrier panel fastener is found in the fastener design with a head type E11-5F11. The design has no RMA. Laminated is shown on the attachment for the carrier panel. The fastener features are similar to the panel. The fastener features include a single row of holes and a single row of threads.

**Function:**
- Connects the panel to the carrier panel.
- Provides mechanical attachment.

**Effect:**
- Reduces stress concentration.
- Improves longevity.

**Advantages:**
- Simplified installation.
- Reduced weight.

**Disadvantages:**
- Limited application.
- Increased cost.

**Notes:**
- Requires additional testing.
- Incorporates new materials.

**References:**
- 8-12-03: Original Document.
- 10-11-15: Revised 8-12-03.

**Figures:**
- Figure 5.1: Elevon Cove Carrier Panel Fastener Detail.
- Figure 5.2: Cross Section Through Elevon Cove Carrier Panel Fastener Detail.

**References:**
- 8-12-03: Original Document.
- 10-11-15: Revised 8-12-03.

**Figures:**
- Figure 5.1: Elevon Cove Carrier Panel Fastener Detail.
- Figure 5.2: Cross Section Through Elevon Cove Carrier Panel Fastener Detail.

10. Elevon Cove Seals

**Description:**
The elevon cove seal needs to be maintained in a TPS failure. It is unique in that it is designed with a known hot gas leak path. The design has no RMA. Laminated is shown on the attachment for the carrier panel. The fastener features include a single row of holes and a single row of threads.

**Function:**
- Connects the panel to the carrier panel.
- Provides mechanical attachment.

**Effect:**
- Reduces stress concentration.
- Improves longevity.

**Advantages:**
- Simplified installation.
- Reduced weight.

**Disadvantages:**
- Limited application.
- Increased cost.

**Notes:**
- Requires additional testing.
- Incorporates new materials.

**References:**
- 8-12-03: Original Document.
- 10-11-15: Revised 8-12-03.

**Figures:**
- Figure 10.1: Elevon Cove Seals Carrier Panel Fastener Detail.
- Figure 10.2: Cross Section Through Elevon Cove Carrier Panel Fastener Detail.
Orbiter Design Concerns

Findings:
- UA team has uncovered additional orbiter design and maintenance concerns that should be addressed.
- Frank Buzzard note to Mike Kostelnik indicates concurrence with all 10 items included in UA briefing.
  - First 6 items included in RCC and Tile portion of the Matrix.
  - Remaining 4 items included in this briefing.

Recommendations:
- Implement UA recommendations as described.

Orbiter Design Concerns

Documentation:
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<th>Orbiter Service Life</th>
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<td>Service Life of the Shuttle Fleet</td>
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Orbiter Service Life

- **Action / Issue:** Determine knowledge of OV-102 service life capability
- **Background / Facts:**
  - Comparison of key parameters used to determine orbiter structure service life to the most current fatigue loads spectra (PE Cycle 8.0) is documented in RSS99D0510D, "Space Shuttle Life Tracking", March 2003
  - Includes all missions from 1981 through February 2003 spanning STS-1 through STS-107
    - OV-102, Columbia, 28 flights
    - OV-103, Discovery, 30 flights
    - OV-104, Atlantis, 26 flights
    - OV-105, Endeavour, 19 flights

Parameter Comparisons

- OV-102 orbiter lift-off weight is within fatigue spectra although rate of occurrences at 260K more than expected

Parameter Comparisons

- OV-102 C.G. location is within fatigue spectra although a more forward shift from expected usage

Parameter Comparisons

- OV-102 max Q is well within the fatigue spectra
Parameter Comparisons

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OV-102 Q-beta is within fatigue spectra although rate of higher occurrences greater than expected - warrants re-evaluation.

Parameter Comparisons

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OV-102 right wing root bending moment is indeterminate due to number of missing flights - warrants re-evaluation.

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OV-102 left wing root bending moment is indeterminate due to number of missing flights - warrants re-evaluation.

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OV-102 inclination angle well within fatigue spectra.

Parameter Comparisons

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OV-102 orbiter landing weight within fatigue spectra.
Parameter Comparisons

Wing Heating Load

- Background / Facts:
  - OV-102 had the highest predicted wing heating load for a location near the wing leading edge
  - Maximum heating load: OV-102 was 1.3 to 1.1 times higher than the other orbiters
  - Average heating load: OV-102 was 1.15 times higher than the other orbiters
  - OV-102 peak structural temperatures significantly less than certification peak temperatures
  - Wing bottom: 190 versus 326 F
  - Fuselage: 244 versus 325 F

Spectra Comparisons

PE Versus 5.4

- Background / Facts:
  - At the request of the CAIB (reference RFI B1-120), 9 wing and vertical stabilizer control points crack growth life predictions were determined using the certification spectra (5.4) and compared to the current spectra (PE)
  - PE spectra 1.4 to 1.6 times more severe for wing bending moment
  - PE less severe for vertical stabilizer bending moment
  - Comprehensive analysis update performed for the airframe structure using the PE spectra (CAIB conducted spot check review)

Orbiter Actual Usage

- Findings:
  - Wing root bending moment results were not determined prior to STS-51
  - Parameters obtained and summarized in the Life Tracking report are not utilized to determine mission life capability (crack growth lives) for each orbiter based on actual usage
  - Fatigue testing of the wing structure has not been performed
  - Fatigue spectra appears to be adequate for near-term operations given the number of missions achieved (30 versus 100), however the spectra may need to be updated to safely achieve 100 missions

Orbiter Actual Usage

- Recommendations:
  - If possible, fill in the missing wing root bending moment data and re-evaluate adequacy of fatigue spectra
  - Carefully monitor the trends of the following parameters: liftoff weight, C.G. location, ascent Q-beta, ascent wing root bending moment
  - Develop the capability to determine mission life capability (crack growth lives) for each orbiter based on actual usage

- Documentation:
  - Responses to RFI's 120 and 195
  - Briefing by C. Modlin, "Orbiter Structural Life", 23 June 1992
Aging Structural Issues

- **Action / Issue:**
  - Aging and Corrosion

- **Background / Facts:**
  - Orbiter designed as maintenance-free for 10 years—all are now older than 10 years
  - Spar is aluminum honeycomb (known to be corrosion prone) in service for 24 years—concerns about galvanic couple between spar and IN718 or A-268 that could lead to degradation
  - Cracks corrosion known to occur on other shuttle locations with 2024-T31
  - 200 doubters reported on OV-102 in response to corrosion damage
  - Anecdotal evidence indicates that chromates leach out of primer after 6-12 years

Orbiter OMRS Corrosion Anomalies at KSC

- **Background/Facts (cont'd):**
  - Corrosion Problem Reports (PRs) are on the Increase

Orbiter Body Flap Cumulative Corrosion Occurrence versus Age

- **Findings:**
  - Corrosion is on the rise

- **Recommendations:**
  - Ascertain parameters that contribute to the aging of corrosion protection materials and processes
  - Chromate leach rates
  - Effect of chemical/thermal/mechanical environments and age
  - Quantify CPC efficacy and limitations
  - e.g., Replication frequency and outgassing
  - Expand use if appropriate
  - Continue to trend corrosion problems and address problems as early as possible

Orbiter Corrosion

- **Recommendations (cont'd):**
  - In order to better establish inspection requirements for corrosion based on environmental exposure, it's important to establish corrosion rates via test for environments, materials and structural configuration specific to the orbiter.
  - USAF and Navy aircraft structure very similar in construction to the orbiter. It may be beneficial to review their corrosion prevention and control practices.
  - Recent USAF and Navy R&D efforts aimed at providing practical modeling techniques for corrosion may also provide insight into the corrosion problem.
  - A USAF Air Mobility Command sponsored program developed an approach to ascertain the Economic Service Life for the KC-135. Their, and similar efforts by others, may be applicable to the orbiter.
Corrosion Near Aft End of Crew Module

- **Action / Issue:**
  - Corrosion found on and near forward fuselage (Xₖ582) and was left unrepaired
- **Background / Facts:**
  - Xₖ582 is a frame near the aft end of the crew module
  - Corrosion found and repaired on forward side of X₀ 582
  - Corrosion "monitored" but not repaired near X₀ 576 (slightly forward of X₀ 582)
  - White corrosion was not removed, CPC was applied to forward fuselage floor
  - Use of CPC not straightforward; specialized application process required because outgassing may occur and interfere with Star Tracker

Location of Xₖ582 Corrosion

- **OV-102 Corrosion Xₖ 582 Bulkhead to floor**
  - Using video borescope, corrosion found on lower forward fuselage skin panel and stringer areas. Extensive rework and corrosion protection of "582" bulkhead forward surface was accepted for unrestricted use.

  - In addition to "582" frame, borescope inspection revealed suspect corrosion (Xₖ 576) on visible rivets and on the sides and feet of hat section stringers.
  - This PR was deferred due to the inability to fully access the area in question to effect a repair. The condition is to be visually assessed on a recurrent basis.

Corrosion Near Aft End of Crew Module

- **Findings:**
  - Access to area between crew module and outer hull difficult to access for inspection and repair
  - Concern that unmitigated corrosion could progress and degrade structure below minimum safe level
  - OV-102 lower fuselage construction in area forward of Xₖ582 was unique and caused it to be more susceptible to corrosion
  - Corrosion cannot be eliminated as a potential degradation mechanism on the other orbiters

- **Recommendations:**
  - To better understand potential impact, perform analysis of corrosion susceptibility, growth and damage consequences relative to factors influencing corrosion
    - **Material**
      - Alloy, Temper, orientation, product form, anodized, clad/unclad
  - Fasteners
  - Type, finish, AMS, wet/dry installed
  - Coating
  - Conversion coats, primer, CPC
  - Mechanical load orientation
  - Blanket insulation
    - Attachment material and method of attachment
    - Blanket material
  - Environment
    - Accelerated fire suppression activation, CPF environment, rain exposure, pad exposure
Corrosion Near Aft End of Crew Module

- Recommendations (cont'd):
  - Develop inspection procedures going beyond borescope
  - Develop repair procedures in areas difficult to access
  - Be innovative; review other industry's practices where repair in
difficult to access areas is required (i.e. nuclear community)
Fastener Environmentally Assisted Cracking (EAC)

- **Action / Issue:**
  - Potential for environmentally assisted cracking of Inconel 718 and A-266.

- **Background / Facts:**
  - A-266 bolts are used as fasteners for LESS components.
  - Microbial or fungal corrosion can occur within an environment that contains carbon and a source of water such as condensate. A product of this corrosion process is acid that could degrade Inconel and A-266.
  - Other forms of environmentally assisted cracking are also possible.

Material of RCC Attachment Hardware

- **Attachments:**
  - Inconel 718 (A-266)
  - Lower Access Panel

LESS Lower Carrier Panel

- **Material:** Aluminum 2219-T8511 or 6061-T651

Recovered Spar Fitting

- Item 9413
  - Left wing lower spar fitting at panel 10
  - Bolt used to attach lower carrier panel

Carrier Panel A-286 Bolt

- Fracture surface of bolt (from Item 9413)
  - Side view of bolt (from Item 9413)
Carrier Panel A-286 Bolt

Higher magnification photos of fracture surface of bolt from Item 9413

Fracture Surface

Similar features found on bolt from left wing lower spar fitting at panel 17

Fracture surface of bolt from Item 866

Side view of bolt

OV-102 Debris Sampled

Lower Spar Fittings Carrier Panel bolts

Fastener Environmentally Assisted Cracking (EAC)

Findings:
- Failure mode of recovered carrier panel bolts is consistent with high-temperature failure; failure is not due to EAC
- Current design and maintenance practices leave components at greater risk for corrosion

Recommendations:
- Obvious galvanic couples between aluminum and steel alloys should be avoided or clearly mitigated
- The use of TFE and MoS2 should be expressly forbidden in assembling components
- The use of primers and sealants such as RTV 669 and Korson should be reviewed with respect to their possibly accelerating corrosion in real environments including in tight crevices.

Fastener Environmentally Assisted Cracking (EAC)

Recommendations (cont'd)
- The negligible and compressive stresses presently occurring in A286 bolts provide protection against failure; assuring the continued presence of such low-to-negative residual stresses should be part of acceptance and qualification procedures.
- The detailed general and impurity chemistry of all paints, adhesives, and sealants should be reviewed periodically at the ppp to ppm concentrations, and such results should be reviewed from a corrosion point of view.
- The procedures and criteria for qualifying materials and coatings from a corrosion point of view should be reviewed for their relevance and adequacy.
- A substantially higher level of understanding and appreciation of damaging effects of all relevant ambient and applied environments on critical materials should be incorporated into the design and maintenance of the orbiters.
Maintenance Wiring Inspections

- **Action / Issue:** Kapton wiring, currently used in orbiters, poses inspection/maintenance challenges. Assess NASA actions to address these challenges.
- **Background:**
  - Each orbiter contains approximately 852,000 feet of wire.
  - Amounts vary depending on modifications/instrumentation.
  - Most of the wiring is insulated with Kapton.
- **Findings:**
  - Kapton (MIL-W-81381) refers to a type of insulation (technical name: aromatic polyimide) originally developed by DuPont in the 1960s.

Findings (cont'd):

- Major causes of insulation failure (splitting/tracking/fitting):
  - Improper installation during manufacture (unknown at the time), such as routing (light bend), clamping (too tightly), or positioning wires against burnt screw heads/twist tails/strip edges; causes insulation wear/failure due to vibration and/or maintenance.
  - Wire stress during inspection/maintenance: repositioning by technicians for access and/or unintentional actions (stepping).
    - Determined to be the single largest cause on orbiters.
  - Exposure to elements such as solvents/erosive/thermal/moisture.
  - Parallel, extensive Al study (1998) concludes most problems due to
design, installation, and maintenance.
  - OV-102/STS-93 (Jul 99) incident raised awareness: loss of power to two of six Main Engine Controller computers 5 sec after liftoff.
  - Investigation identified root cause as damaged wire.

Findings (cont'd):

- OV-103 currently in OMM/undergoing remainder of wire inspection.
  - Total discrepancies (stand down + OMM) nearing OV-102 proportions.
  - Arc track testing using orbiter circuit protection/wiring displayed limited track lengths; worst case = 6.5 inches.
  - Current masts include separating all critical wire paths from main bundles and individually protecting them.
  - Numerous tests indicate Kapton is still the leading choice for orbiter environment despite development of hybrid insulators.
  - Development of improved inspection equipment/techniques (i.e., supplement visual) continues in the aviation community.
  - Wholesale replacement, whether in military/commercial aviation, or the orbiter fleet, is costly.
  - Hybrids used on new build 8737/8757F-15/22 (post-1995).

Findings (cont'd):

- NASA has taken numerous corrective actions since STS-93:
  - Extensive inspections/corrective actions, starting with OV-102's J3
    OMM (Sep 99); 1st month after roll-in, complicated OMM.
  - Other orbiters grounded for inspection (partial), full inspections to be completed during scheduled OMMs.
  - Results of OV-102/J3 OMM used to refine inspection/documentation methodologies (more comprehensive/issue-specific tracking).
  - Improvements made in technician/inspector training and certification, maintenance procedures (e.g., calibrated crimpers).
  - Wiring inspection now required during any ground processing actions.

Findings (cont'd):

- Modifications either complete, in progress, or scheduled show ongoing efforts to mitigate wiring problems:
  - MCR 19448: Orbiter Wire Protection Enhancements addressed
erouting of redundant/Crit 1 wires, 127 cases ID'd.
  - MCR 19537: Orbiter Wire Redundancy Separation corrects all 127.
  - MCR 19566: AC Bus Separation separates critical wires to DS; pre
    MCR 23167: Arc Track Protection continues efforts, Rev 1 for OV-
    102/FB-19 (STS-107).
  - Approx. 2,000 feet of orbiter wiring is inaccessible.
    - Primary below crew module.
    - No plan to inspect the life of the orbiter.
    - No technician traffichands on maintenance due to inaccessibility.
    - NASA has confirmed, thru USA and Boeing, no Crit 1 wiring in
      inaccessible areas.
    - Concern: installation-induced problems over 20+ yrs of service.
**Maintenance Wiring Inspections**

- Conclusions:
  - NASA has taken extensive action to mitigate orbiter wiring-related problems
  - Kapton issues (especially age-related) are still not fully understood
- Recommendations:
  - Continue as expeditious as possible implementation of all wiring-related inspections/mods
  - Inspect/track/monitor wiring to determine aging effects
  - Develop plans to inspect inaccessible wiring as part of the Shuttle Service Life Extension Program
  - Assess the adequacy of Kapton wiring inspection/maintenance in non-orbiter areas, such as RSRM/ET and SRB/MLP separation bolts

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**Maintenance Added Wiring Insulation/Separation Examples**

Examples of Harness Protection

- Convulated Tubing
- Teflon (PTFE) Wrap Sheet
- Cushioned Clamps
- Silicon Rubber Extrusion

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**103 J3 Wire Discrepancies Summary**

- Total Discrepancies: 1783
- Wire Discrepancies by Type:
  - Electrical: 1238
  - Mechanical: 390

---

**Maintenance - Wiring Inspections**

Red Dashed Lines Indicate Inaccessible Wiring
Orbiter Environmental Exposure

- Action / Issue: Review/assess orbiter exposure to elements
- Background / Facts
  - OV-102 cumulative launch pad weather exposure: 3.3 years
  - Longest single exposure: STS-35/164 days (Apr-Dec 90)
  - Exposure to elements (rain, dew, salt air) has a negative impact
  - Corrosion to structure, oxidation/damage to KCC (suspected), wiring, etc.
- Findings:
  - Orbiter total exposure time (less ~102) varies from 2.1 to 2.9 years
  - OV-102 leads fleet in total exposure time, but not in total launches
  - OV-102: 28 launches; OV-103: 30 launches
  - Rollovers/rotates/rollbacks due to launch scrub, follow-on maintenance, & ops checks contribute to prolonged exposure

Orbiter Environmental Exposure

- Findings (cont'd):
  - Besides pad exposure, most notable vulnerability is during mate/launch/entry; three incidents noted
  - Sep 99: OV-102 caught in rain at KSC during mating
  - 128 lbs/176 gals removed after arrival at Palmade
  - Feb 01: OV-102 caught in rain at Palmade after mating
  - 147/45hale could only be partially hangared (see picture)
  - 112 lbs/14 gals removed after arrival at KSC
  - Feb 01: OV-104 caught in rain during mating at Edwards AFB
  - 1,600 lbs/200 gals removed after arrival at KSC
  - "Was fuelage under bay 6 full of standing water"
  - Fine notes deep storage tank of 1307 bbl/day
  - Mate/debate ops highly vulnerable to inclement weather
  - Lengthy operation; no shelter at any location
  - No positive pressure inside shuttle, as at pad

Orbiter Environmental Exposure

- Findings (cont'd):
  - Environmental (specifically weather) exposure is clearly outlined in RTO/M0101.100, Adverse Environmental and Lightning Monitoring at LC99
  - Includes guidance on actions to be taken to minimize exposure to rain/hail/winds/freezing temps/tornadoes, etc.
- Recommendations:
  - Emphasize strict adherence to existing guidance
  - Take every opportunity to avoid/minimize/reduce exposure
  - Review/analyze launches where exposure was significantly over or under the mean (e.g., +1 standard deviation) for lessons learned
  - As some amount of exposure is unavoidable, an intensive corrosion program (inspection, treatment, prevention) is a must
  - See related "Action/Issue" slides on Corrosion and Service Life Extension Program (SLEP)
Orbiter Environmental Exposure
Corrosion Related PRs-Body Flap Cove Area

Cumulative Corrosion Age

Orbiter Environmental Exposure
Rollover Constraints

Rollover Constraints:
- LTO within 2NM
- Temp < 36°F
- Any Precipitation
- On transporter: Wind > 42 Peak 64 Kts
- On landing gear: Wind > 40 Peak 60 Kts

Orbiter Environmental Exposure
Mate / Demate Ops Constraints

Mate / Demate Constraints:
- Lightning within 5 nm
- Rain, Any Size
- Any precipitation
- Surface winds: Depends upon direction
- Surface Temps < 60°F
- for more than 2 hrs
Maintenance
Aging Vehicle/SLEP

Findings:
- Funding request in May for initial studies to identify tasks in most crucial sustainment programs. Mid-Life Recertification (MLR), Flight Crew, MSL, and Cooling Systems. MLR will define tasks to be completed to ensure the STS is fit to continue use through unforeseeable life span.
- Proposals expected to identify necessary upgrades to structures and subassemblies to assure safe operations as well as recommendations for maintenance and inspection programs.
- MLR funding unallocated.
- Significant effort to prioritize previously identified candidate programs and add to budget request.
- Higher headquarters supportive but concerned over financial impact of CAIB recommendations.

Recommendations:
- Sustained program needs a clearly articulated goal in terms of sustainment objectives. NASA has not focused on a long-term financial commitment.
- NASA should consider a sustainable development roadmap and develop a strategy to resolve sustainability issues.
- Restructure the SLEP mission. New systems and programs establish this program as the central repository for nearly any shuttle related project. This will leave SLEP vulnerable to budget cuts and dilution of NASA's ability to resolve sustainment issues.
**Maintenance**

**Aging Vehicle/SLEP**

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**New Items: Total Funds (millions) for each Fiscal Year:**
- FY03: N.A.
- FY04: 40
- FY05: 62
- FY06: 72
- FY07: 82
- FY08: 92
- FY09: 102
- FY10: 112
- FY11: 122
- FY12: 132
- FY13: 142
- FY14: 152
- FY15: 162
- FY16: 172

**Total:** 1,020

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**Recommendation 02-1a:**
- Through proactive review, revalidate and revise the criteria for critical ground and flight systems recertification.

**Recommendation 02-1b:** Based on the findings and technical information garnered from the recertification process, validate and update the maintenance, test, and inspection requirements.
OV-102 Hard Landing

- Background / Facts:
  - Main gear impact was highest sink rate in flight history
  - Estimated max of 6.7 fps through camera data
  - Crosswind: 4 – 11 kts range
  - Worst case (11) used in assessment
  - Landing weight: 233,000 lbs
- Combined sink rate/wind/landing weight exceeded design criteria
  - Design criteria of 5.97 fps versus estimated 6.7 fps

Findings:
- Design criteria not equally critical at all landing weights
  - Design criteria exceeded by 12%
  - Design criteria exceeded for design load
- Calculated MLG loads/reviewed & approved by Loads Panel/Load factors used in structural analysis
  - Reconstructed load less than half of design load
  - Energy comparison explains why load capacity can be higher than design
- MADs flight strain data confirmed accelerations/analytical conclusion
  - Reviewed/approved by Orbiter Structures Team 14 Jul 98

Group Recommendations:
- None. Eliminate as a causal factor.
### Maintenance
#### Structural Issues - Hypergolic Spill

- **Action / Issue:** Hypergolic Fuel Spill (McDonald-Chehman letter)
- **Background / Facts:**
  - SIAT learned of hypergolic fuel spill 20 Aug 99 at KSC
  - Occurred during OV-102 prep for shipment to Palmdale
  - Issue briefed to Shuttle Operations Advisory Group 1 Nov 99
- **Findings:**
  - 2.25 oz. dripped from GSE onto left wing inboard eleven trailing edge
  - Spill cleaned, 3 lines removed for inspection; no damage found
  - USA employees at KSC received training; GSE improvements proposed to minimize risk of future spill
  - Quick disconnects now separated at vehicle/GSE interface only
  - Permanent panels now installed in each ODF, eliminates multiple QDs and flex lines on interface and test panel for each job
- **Group Recommendations:**
  - None; spill was small/cleaned/assessed no effect on TPS or wiring

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Maintenance
Paper Work Review

- **Action / Issue:** NASA's review of STS 107/109 paperwork showed that current WAD accuracy may not be adequate to assure CuFR.
- **Background:** CAIB requested NASA explain the methodology and summarize their findings from the paper work audit with emphasis on how they will use them wrt trends/corrective actions/applicability.
- **Findings:**
  - Review of subsystem WADs is ongoing. Early results reveal many "Findings" and "observations" in -107/-109 records
  - "Finding" = "discrepancies that impact the technical execution of the work" per KSC/SCIData Processing Review Team Guidelines and Criteria, Rev G.
  - Ex: Incorrect guidance provided by the author/engineer and failure to document corrective action or initiate PKMM.

**Maintenance
Paper Work Review**

- **Findings:**
  - New WADs will be reviewed by one to three people (depending on the system) who will sign it or stamp before being issued
  - Monthly sampling of WADs called Technical Accuracy Measurement
  - Completed WAD steps may be reviewed by USA & NASA QA
  - Closed WADs undergo several review layers by supervisors, USA and NASA QA, engineers before passed to Quality Data Center
  - No apparent documentation of findings outside PRACA if relevant
- **Recommendations:**
  - SSP program management should consider review of STS 114/115 records prior to flight
  - NASA should institute a system to review and evaluate all CRIT 1 and 2 systems paperwork and sample the rest.
  - Build a documentation quality control process to sample and document errors to use in trend analysis and process feedback.
Fire (Pyro / Wiring / etc.)
OV-102 Unique Wiring Configuration

- **Action / Issues:** Determine reason for OV-102's unique wiring configuration (left wing) and its role in data loss leading up to LOS
- **Background / Facts:**
  - OV-102 wiring outboard of MLG wheel well routed in 4 large bundles;
  - other orbits have 7 small bundles
- **Findings:**
  - As the first operational orbiter, OV-102 had additional instrumentation; nearly 90% of wires routed through this area associated with OEX data gathering and/or disconnected systems
  - Bundle securing method changed from clamps to tape straps in later orbiters; tape less able to secure large bundles – additional smaller diameter bundles (0.5 in or less) required
- **Group Recommendations:**
  - Not causal, but inclusion in OEX data analysis/sequence of events leading up to LOS will enhance investigation
  - Role in data loss sequence TBD; NASA wire heating tests ongoing

Fire (Pyro / Wiring / etc.)
Internal Hazard

[Image of OV-102 and OV-103 with wiring bundles shown]
## Orbiter Major Modification (OMM)

**Action / Issue:** Review/assess past OMM performance; movement of OMMs from Palmdale (PD) to KSC; and OV-102’s most recent OMM, identify significant issues/concerns.

**Background / Facts**
- **NTS 07702, Volume III:** Requires each orbiter to undergo an OMM every 8 flights or 3 years.
  - Orangers are removed from service for varying amounts of time, depending on work to be performed.
  - Length of OMM driven more by mods than inspections.
  - Work includes baseline nmrts (timeliness changes), routine inspections (structural, special inspections (wiring), mods, deferred work, and correcting "dumbbells"
  - OMMs typically involve more intrusive inspections/maintenance/mods than during AIPs (down-up-revision processing).
  - OMM are a subset of OMMs (Orbiter Maintenance Down Period), which also include AIPs (Up-mission Processing).

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## Orbiter Major Modification (OMM)

**Background / Facts (cont’d)**
- 10 OMMs to date.
  - 8 at PD (OEM), including OV-102 “AA” (removed from test/development to operational configuration).
  - 2 at KSC: OV-103/J1 (2-8/92) and OV-103/J3 (in progress).
  - Durations (as measured from landing to launch) have ranged from 5.7 months (OV-103/J1) to 15.5 months (OV-104/J1).
  - Wide variation in durations result from variations in OMM content.
  - Historical challenges meeting flight/3 year interval.
  - OV-102: 8 flights/4 years between J2 and J3.
  - OV-103: 9 flights/4.5 years between J2 and J3.
  - OV-105: currently 8 flights/5 years, next OMM: 11 flights/4 years.
  - OV-104: 12 flights/8 years based on manifest & Oct 05 OMM.

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## Orbiter Major Modification (OMM)

**Findings:**
- OMM location weighed since early 90s: PD or KSC?
  - NASA Ig (95): Cost savings at KSC, but due to complexity of scheduled work and launch schedule, leave next 2 at PD.
  - NASA Ig (98): PD costlier, but “risk… greatly reduced,” “risk… at KSC outweighs potential cost savings.”
  - Review due to increased use of resources (personnel, infrastructure).
  - JSC Sys Mgr Office conducted significant savings between worst case at KSC and best case at PD.
  - Feb 02: NASA approved OV-103 OMM (Sep 02) at KSC.
  - Short term factors cited: FY03 budget shortfalls, FY02 impact.
  - Long term: Life cycle cost reduction.
  - Slightly decreased launched rate from 1/1 (7) to 0/2 (6) by a 2ndary factor

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## Orbiter Major Modification (OMM)

**Findings (cont’d):**
- Workforce/labor expenditures appear more efficient at KSC, but too early for any definitive conclusions.
  - Last 4 PD OMMs: 324 to 448 (blue/white collar) equivalent personnel (EP): 363 average.
  - Additional KSC augmentation: 30-40 techs/inspectors/engineers.
  - Current KSC OMM (last 7 months): 236 EP projected, averaging 301.
  - No other recent OMMs for comparison (last OMM 10 yrs prior).
  - Potential reasons for KSC efficiency compared w/PD.
    - Larger workforce allows flexibility in shifting resources to match peaks/valleys.
    - Steadier overall workload (not just OMMs) keeps worker proficiency at a higher level; workers not laid off/off to other jobs as at PD.
  - One concern voiced by several managers: ability of fluid workforce (especially engineer) to focus.

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Orbiter Major Modification (OMM)

Findings (cont'd):
- Workforce experience levels more stable at KSC due to fewer workload fluctuations
- 176 additional workers hired at KSC for OMM relocation, assimilated throughout entire workforce (1,900) to minimize training load/impact of inexperience
- By contrast, 85% of PD workforce (324) during OV-102/J3 had prior OMM or orbiter manufacturing experience
  - Some experienced personnel strategically placed in other Boeing jobs to preserve expertise, then recalled for OMMs
  - Others laid off after OMMs, refilled prior to next OMM
- As OV-102/J3 requirements/workload increased, the workforce grew to 500, experienced personnel were quickly tapped out, and experience dropped to 58%: time spent training new/experienced workers increased, including on-the-job training

Orbiter Major Modification (OMM)

Findings (cont'd):
- Support equipment capability comparable; slight advantage at PD WRT large component removal/installation due to OEM
  - Ground Support Equipment newly moved between sites
- Last PD OMM: OV-102 J3
  - Roll-in: 26 Sep 99, roll-out: 24 Feb 01
  - Initial duration: 935 days; actual: 517 days (76% growth)
  - Capsule delay, roll-out achieved with 98% of work completed
  - Major mods included MEDS (glares cockpit), GPS, wireless video
  - Large growth in requirements/robible ones (see chart)
    - HEDS IA KS-7309 (3/18/01) perspective
      - "Poor performance on NASA, USA, and Boeing" (schedule/cost)
      - "Work quality very good to excellent" (product)
      - Offers MANY important lessons learned applicable to the future

Orbiter Major Modification (OMM)

Findings (cont'd):
- HEDS Independent Assessment (IA) of OV-102 OMM
  - Contractor estimated 331-day flow; ESP directed 390; contractor initially assessed schedule as "red", though management subsequently agreed based on anticipated efficiencies & revised schedule risk assessment
  - PD adequately staffed (initially) for the OV-102/J3 OMM, but unforeseen problems/def work quickly exceeded capabilities
  - OMM requirements increased by 100% over initial planning (MSRR), and by 50% after roll-in: high by comparison with other OMMs (see chart)
  - Wire inspection added 1-month after roll-in, fast track extension based on expectation of 500-700 anomalies, actual 4,000+ anomalies, ESP allowed a second fast track extension inspection chrt revised 6 times
  - Other technical surprises (e.g., cold plate corrosion) and procedural problems (e.g., payload bay door rigging) exceeded scheduled time by more than double and slipped power-on testing

Orbiter Major Modification (OMM)

Findings (cont'd):
- Additional HEDS IA determinations
  - OMM management suffered due to an inexperienced flow manager
    - Message to ESP was regularly optimistic re: key milestones
    - Flow manager used a new, unproven scheduling tool that proved inadequate, returned to previous tool after 10 months
    - The rapidly rising number of anomalies made integration of workload scheduling increasingly difficult
    - Integrated scheduling meetings were not held frequently enough to keep abreast of changes (weekly vice daily), daily slips 12-months into OMM
    - The large volume of PIRs generated by nonconformance inundated the system and contributed to management difficulties
    - OMM problems were exacerbated by the Program Office taxing the process over to USA without a structured insight function in place

Orbiter Major Modification (OMM)

Findings (cont'd):
- OV-103 J3 OMM still a challenge
  - Requirements growth continues: 20 mods originally scheduled due to budget limitations and conservative approach (first KSC OMM); however, mods alone have increased to 84 (200%) by mid-April (67% thru OMM)
  - 24 additional mods being held to not overload capability
  - Despite growth, overall OMM flow well managed (compared to OV-102)
  - AF Depot Maintenance Team benchmarking visit to KSC in Jun
    - Invited by NASA Code M to assess OMDP/OMM processes
    - Benchmark areas: documentation, policy/procedure adherence, logistics (NSLD) support, "ship side" engineering support, safety, communication
    - Areas requiring review/increased attention
      - Requirements definition plans (e.g., MVP, OMID, OPRD) lack a defined loop feedback to process to routine/systematically adjust
      - Plans and scheduling can benefit from increased stability
**Orbiter Major Modification (OMM)**

**Findings (cont'd):**
- AF Depot Maintenance Team/OMM areas requiring review (cont'd):
  - Orbiter sustainment roadmap must be tied into OMM requirements
  - Gov/contractor relationships require review to ensure the right OMM "behavior" is being incentivized

**Conclusions:**
- While there are specific baseline elements, no two OMMs are alike; variations occur as orbiters age (wiring inspection, cold plate corrosion), as mission requirements change (reconfiguration for MIR and, in some cases, due to lack of funding; improving schedule and funding stability can help reduce process variation and aid in better planning/scheduling and less turmoil)
- Increasing OMM intervals as orbiters age is counter to industry norms; for high performance systems, it raises even greater questions

**Orbiter Major Modification (OMM)**

**Recommendations:**
- The Program Office MUST work to achieve greater stability in OMM-scheduled work, particularly the number of mods (biggest driver of schedule/workload variation; a continually changing schedule (time consuming) creates unnecessary turmoil/stress and increases the potential for quality escapes
- Managers (NASA/USA) MUST understand workforce/facilities capabilities, schedule to those capabilities, and take necessary actions to avoid exceeding them (ref. Capabilities Assessment briefing)
- The SSP Office MUST determine how it will effectively meet the challenges of inspecting/maintaining an aging orbiter fleet prior to increasing the OMM interval
- NASA/USAF benchmarking efforts should be continued using the same personnel as much as possible for continuity

**Orbiter Major Modification (OMM) History**

**Orbiter Modifications OMM vs. Flow**

<table>
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<tr>
<th>ORBITER</th>
<th>MODS IN OMM</th>
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<td><strong>TOTAL</strong></td>
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Report Volume V October 2003
Orbiter
Launch – Ascent

15-1  STS-107 Key Loads Parameters Versus Design and Experience
15-2  STS-107 Ascent Loads (DOLILU)
15-3  STS-107 OEX Ascent Data
STS-107 Vs Past Experience

- **Action / Issue:** Compare STS-107 key parameters to past experience and design limits
- **Background / Facts:**
  - STS-107 key parameters extracted from RSS99D0510D. “Space Shuttle Life Tracking”, March 2003

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STS-107 Vs Past Experience

STS-107 Versus Fleet Experience
Orbit Weight at Liftoff and Landing

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STS-107 Vs Past Experience

STS-107 Versus Fleet Experience
Apogee Max Q

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STS-107 Vs Past Experience

STS-107 Versus Fleet Experience
Wing Root Bending Moment during Ascent
STS-107 Vs Past Experience

- **Findings:**
  - All STS-107 key parameters compared have responses less than the maximum experienced in the fleet and the design limit values
  - No issue discovered to date
- **Recommendations:**
  - Incorporate information into Ascent Integrated Scenario
STS-107 Launch/Ascent

Action / Issue:
Review STS-107 structural responses during ascent

Background / Facts:
- Structural response of Shuttle depends on a combination of:
  - Flight control commands
  - Shuttle responses (a and b) changes, gimbals angles, LOX strag, etc.
  - Environment through which Shuttle ascends (wind, etc.)
- Guidance commands in the Day of Launch Update (DOLULU) provide input to flight control software
  - Inputs to DOLULU: measured winds, atmospheric data, vehicle config.
  - What DOLULU targets: angle of attack (a), angle of sideslip (b), dynamic pressure (q) as function of Mach number
- DOLULU Outputs: guidance commands to control
  - Vehicle pitch & yaw attitudes
  - SSME throttle
  - SSME & SRB gimbals angles controlled by flight control software
  - DOLULU is used to assure vehicle is flown within an acceptable structural limits envelope

STS-107 Launch/Ascent

L-04:30 and L+00:15 Jimsphere Data

Background / Facts:
- L-04:30 balloon used to build L-04 data
- L-15 minute balloon
- Wind shear failure at Mach 1.5
- Resulted in peak -1.8 deg
data

STS-107 Launch/Ascent

Angle of Sideslip (Beta)

Background / Facts:
- Due to wind shear, the following Shuttle responses exceeded prior flight experience (see next 3 charts)
  - DOLULU 3 & 8 degrees
  - SRB gimbals angles
  - SSME #3 pitch gimbals angle

STS-107 Launch/Ascent

SRB Left Tilt & Rock Gimbal Position

Background / Facts:
- SRB Left Tilt & Rock Gimbal Position
  - Flight Experience STS-22
  - Flight Experience STS-104
STS-107 Launch/Ascent

SRB Actuator Angular Deflections

- Background / Facts (cont.):
  - STS-107 Experience (SRB gimbal oscillations)
  - STS-107 accelerometer & SRB actuators show 0.6 Hz oscillation
  - All missions experience a 0.6 Hz frequency content
    - 0.6 Hz frequency due to LOX leakage and vents
      - Missions 2, 51, 53, 64, 65, 90, 97, & 101 experienced similar oscillations
  - Left & right rock and tilt actuator positions were compared to program experience, Performance Enhancement (PE) mission experience, PE analysis database, and design limits (see next four charts)
STSB-107 Launch/Ascent

Findings:
- Out-of-experience events were within certification limits
- Flight Control System operated as designed
- During the wind shear event at MEL = 57 sec, wind shears, sidelaunch angle, SRB gimbals, and observed & predicted left & right wing loads were all below design limits
  - All wing loads were ≤ 50% of design limits
  - Maximum attachment and orbiter body loads during entire ascent were below design limits
  - Wing instrumentation indicates more cycles on left vs. right wing
- Left & right SRB rock and tilt actuator positions were within design limits

Recommendations: None
STS-107 OEX Ascent Data

- **Action / Issue:** Review STS-107 OEX ascent data for anomalies
- **Background / Facts:**
  - Ascent significant events included:
    - 60 seconds – wind shear occurred at Mach 1.37 at an altitude of approximately 32,000 Feet
    - 82 seconds – foam impacted orbiter wing at Mach 2.46 at an altitude of approximately 60,000 feet

**Graph:**
- Strain gage on front spar behind RCC panel 9
- Strain gage on lower skin or spar at spar #3
- Pressure measurement locations

**Graphs (Laver, Nair):**
- Laver lower surf press (LT)
- Nair lower surf press (LT)
Findings:

- STS-107 wing front spar temperature sensor measurements compared to previous 7 missions show unusual activity.
  - One extra bit drop during ascent through MET=180 seconds.
  - Earliest bit increase during ascent (approximately MET=330 seconds versus MET=600 seconds for others).
  - Two extra bit rise during latter part of ascent.

Recommendations:

- Incorporate information into Ascent Integrated Scenario.
Orbiter Entry

16-1  Effect of Roughness (Keq) on Orbiter Heat Load
16-2  Kapton Wiring
16-3  Premature Firing of Pyrotechnic Devices
Rough Wing Structural Issues

- Action / Issue:
  - Effect of Roughness (Keq) on Orbiter Heat Load
  - Background / Facts:
    - Speculation that OV-102's wing was "rougher"—Keq nearly twice that of other orbiters
    - High Keq causes early transition to turbulent flow and greater heat load (hotter longer)
- Findings:
  - Found that OV-102 Keq similar to that of other orbiters
- Recommendation:
  - Continue to emphasize the importance of minimizing Keq

Boundary Layer Transition

Step and Gap Measurement

- For an unfilled gap:
  \[ s = step \text{ measured from low tile} \]
  \[ w = gap \text{ width} \]
- For locations where the gap is 0.045" or less
  \[ Keq(step) = Keq + 0.045 \]

Measurement Locations

OV-102 Transition History

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Transition time from Entry Interface (sec.)
**Aeroheating**

Maximum Measured Structural Temperatures on Lower Wing

- Maximum 90th Percentile
- Average
- 1st Quartile
- Minimum

For all flights with recorded data

- OV-99
- OV-102
- OV-103
- OV-104
- OV-195

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203
Fire (Pyro/Wiring / etc.)
Kapton Wiring as Causal

- **Action / Issue:** Assess Kapton wiring as a fire/explosion risk to OV-102/STS-107
- **Background / Facts:**
  - Kapton insulation proven to degrade under certain conditions
  - Insulation degradation leads to risk of shorting between wires
  - "Arc tracking" along length of wire
  - Arcing can damage adjacent wires
- **Findings:**
  - In-depth inspection of OV-102 during J3 OMM (Sep 99 – Mar 01)
  - Identified numerous nonconformances (nearly 5,000)
  - Prompted by damaged insulation/wire/insulation failures to two of six main engine controller computers during STS-93 (Jul 99)
  - OV-102 inspection results formed a good baseline for subsequent studies/development of preventive measures
  - Most common cause: work-induced, either during inspection/maintenance
  - Other causes: improper installation (routing/securing) during manufacture; moisture intrusion, chemical spillage

Fire (Pyro/Wiring / etc.)
Internal Hazard

- **Findings (cont.):**
  - Despite numerous ongoing studies of alternate insulators, Kapton still viewed as a leading candidate
  - Various reasons: Kapton does not burn, but carbonizes at approx. 600 degrees C; also lightweight, durable
  - Telemetry from OV-102’s last minutes prior to breakup does not point to Kapton wiring as causal
  - Data from 14 left wing sensors analyzed: hydraulic line/wing skin/wing temperatures, tire pressure, & landing gear down/takeoff position
  - Sensor failure signatures consistent with leading causal scenario of left wing thermal intrusion, NOT with Kapton-associated failure
  - Actual/extend NASA testing immediately following Columbia tragedy verified failure signature analyses
  - Kapton wiring subjected to oven, blowtorch, and arc jet heating
  - Testing analysis for years prior to STS-107 showed Kapton wiring with voltages & low currents associated with orbiter instrumentation (such as in the left wing) have a very low probability of arc tracking

Fire (Pyro/Wiring / etc.)
Internal Hazard

- **Conclusions:**
  - Based on extensive wiring inspections/maintenance/modifications to OV-102 prior to STS-107, analysis of sensor/wiring failure signatures, physical verification of those signatures, and prior Kapton wiring studies, Kapton’s role as causal to Columbia’s loss is highly unlikely

- **Recommendations:**
  - Inspection of remainder of fleet planned/being executed
  - Partial inspection completed on all orbiters during initial grounding
  - Complete inspection to occur during respective OMWs
  - OV-103 currently in progress with expected completion in Apr 04
  - OV-105 to be completed in 04 (inert date accelerated to summer 03)
  - OV-104 must be fully inspected as soon as possible
Fire (Pyro /Wiring / etc.)

Internal Hazard

- **Action / Issue:** Determine conditions necessary for auto-ignition of pyrotechnic devices and their role in STS-107's loss.
- **Background / Facts:**
  - 137 NASA Standard Initiators (NSI) used throughout shuttle
  - 102 units fired during nominal mission
  - 35 units for emergency applications (including landing gear extension)
- **Findings:**
  - Qualification requirement: No auto-ignition with thermal soaking of 425 deg F for 1 hr.
  - Individual component chemicals auto-ignite at 700-750 degrees F
  - Actual cartridge testing (1 Feb):
    - Assets removed from NASA stock; manufactured Feb 84
    - Auto-ignited at 595 deg F
- **Group Recommendations:**
  - While not likely to be causal, pyro cartridge auto-ignition due to wheel well heating must be included/considered for in any failure scenario involving thermal intrusion into the LMLG well
Other Design – Certification

17-1 SRB ET Attach Ring Structure Factor of Safety
SRB ETA Ring

- **Action / Issue:** SRB ET attach (ETA) ring has reduced properties
- **Background / Facts:**
  - Recent material testing discovered strength values less than the design requirement
  - Minimum requirement is 180 ksi
  - Lowest value from 2 S/Ns is 144 and 150 ksi
  - Issue presented during ET tanking meeting on 16 Jan 03
  - SSP CR S09/14986 approved on 16 Jan 03
  - Waived the factor of safety requirement of 1.4, accepted 1.25
  - No full technical review prior to launch of STS-107
  - ETA design life is 40 missions (inspection interval is 13 missions), STS-107 ETA rings:
    - Left: S/N 19, 9 flights prior to launch
    - Right: S/N 6, 12 flights prior to launch

SRB ETA Ring

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    - Right: S/N 6, 12 flights prior to launch

SRB ETA Ring

- **Background / Facts:**
  - STS-107 strength analysis performed using 147 ksi
    - Factor of safety reduced to 1.25 (ET tanking meeting value)
  - MSFC recommended using 136 ksi based on metallurgical assessment in March 2003
    - Factor of safety reduced to 1.16
    - Below design minimum thickness measured on 7 ETA rings in March 2003
    - Strength analysis being revised accounting for hardness test results correlated to strength and actual part thickness
    - Both the current analysis method (linear material properties) and non-linear analysis methods are being utilized

SRB ETA Ring

- **Background / Facts:**
  - Non-linear analysis method (takes advantage of entire material stress-strain response) to determine ultimate strength capability validated by test of specimen shown below
  - Good correlation between predicted and measured strains and failure load was obtained
SRB ETA Ring

### Summary of Original, Revised and Current Strength Analysis

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<th>ETA Ring Area</th>
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<td>7</td>
<td>1.35 (C-Material)</td>
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### SRB ETA Ring

**Background / Facts:**
- Total quantity of SRB ETA rings is 17
- 9 rings were readily available for hardness and thickness measurements (the others require some level of disassembly) and have been completed
  - SnN: 5, 6, 9, 15, 16, 19, 22, 24, and 27
- Strength analysis performed using linear analysis (more conservative) and actual hardness and thickness results
- SnN 16 has a region with a factor of safety less than 1.4 and a region with low hardness results
- The other 8 SnNs have a minimum factor of safety > 1.4
- SnN 15 has a couple of regions with marginal hardness results
- All rings have factor of safety > 1.4 using non-linear analysis method
- 9 rings have completed NDE on critical regions
- All rings will undergo a complete re-baselining NDE, SnNs 9 and 24 are in-work to support first return to flight

### SRB ETA Ring

**Background / Facts:**
- NASA's short-term plan:
  - Complete NDE on 9 installed rings
  - Uninstall the remaining 8 rings if hardness and thickness measurements and NDE
- NASA's long-term plan:
  - Replace ring web plates with new material or material that meets specifications and proper thickness
  - Implementation plans have not been approved by the program

### SRB ETA Ring

**Findings:**
- Short-term plan to include hardness and thickness measurements and NDE of the 8 remaining rings is adequate
- 7 of the 9 rings measured to date appear to be adequate for limited use
- Long-term plan is the best approach, funding and implementation schedule has not been authorized by the program

**Recommendations:**
- Don't use SnN 16 and 15 in their present condition
- Accelerate implementation of long-term plan

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Maintenance Turnaround Work

- **Action / Issue:** Active maintenance of critical technical institutional knowledge and know-how
- **Background / Facts:**- Aging workforce working on an aging fleet
- **Findings:**
  - NASA has a training program to grow workforce with expertise levels commensurate with training and experience
  - Available technical expertise for sustaining NASA OA technicians
  - Continuing education and training
  - Training challenges for existing workforce to adapt to new inspection and maintenance requirements
  - Impact of contractor culture, NASA culture
- **Group Recommendations:**
  - NASA should continue to monitor critical personnel issues

USA Age Distribution

- **USA Proprietary Information**
- **Not for Release**

Workforce Aging

- **USA Proprietary Information**
- **Not for Release**

Engineer Aging

- **USA Engineer Process Age Trends**

Attrition in USA

- **USA Attrition Remains Below Industry**

USA Sources of Staffing

- **USA Proprietary Information**
- **Not for Release**
Transfer Rights

USA, Boeing & Lockheed Service Recognition Used to Facilitate Employee Transfers

* Service with Members (Boeing and Lockheed) is recognized for:

- Vacations
- Leave accrual
- Holidays
- Participation and voting
- Medical, dental, and vision
- Service with another company
**Maintenance Safety & Mission Assurance**

- **Action / Issue:** NASA/USA's Safety & Mission Assurance has had significant changes in workforce & inspection methodology.
- **Background / Facts:**
  - Suffering of Government Mandated Inspection Points (GMIPs) was questionable by numerous testimonies.
  - KSC GMIPs reduced from 44,000 in 99 to 22,500 in 96 to 8,500 now.
- **Observations and interview information:**
  - Need thorough review of quality program requirements (string non-value added tasks but not some critical items) - e.g., hydraulic pump installation, clearning of SREs.
  - Penny wise and pound foolish? (batteries, lights, inspection mirror tools)
  - Yielding to contractor (FOD definition, schedule, nonexistent unscheduled surveillance)
  - Unsupportive quality program management at KSC (instances of having to go to NASA HQ for resolution); dysfunctional organization of “campus”
  - Under scored by SIAT and other recommendations.

- **Observations and interview information:**
  - Abundance of “fly as in” dispositions.
  - Government inspector hiring eval needed (UCMA and NASA PDs).
  - Disgruntled employees at MAF.
  - Safety and security consistently rated strong.
  - Potentially too few government inspectors.
  - Findings:
    - Internal QA review done by SMA, SQMA and some engineering.
    - QA’s role in process improvement through interpretative trend analysis of PRAC and the Integrated Quality Support database is inconsistent and not integrated between the players.
    - NASA inspectors inconsistently use the Hux or reject stamp for jobs cleared out by SQMA (testimony given to CAS staff).
    - Consequently, NASA SMA has no means of tracking/monitoring for use as evaluation tool for personal training and assessment.

- **Findings:**
  - NASA involvement beyond GMIPs is very limited. Sampling of routine or non-critical tasks not formally done.
  - GMIPs review process is ad hoc with no regular methodology for review of historic data to adjust QA emphasis.
  - SMA manning levels dropped due to retirements and moves to engineering posts without replacement.
  - Interviews:
    - KSC – with additional quality inspectors (several suggested by previous interviewees), and the head and deputy of the quality program.
    - MAF – with additional quality inspectors (several suggested by previous interviewees).

- **Recommendations:**
  - Broaden SMA inspections to include statistically-driven sampling of all maintenance-related processes.
  - Should go beyond GMIPs specific events to validate USA Quality inspection results and verify work quality before close out.
  - Include a process to sample/validate documentation of maintenance for completion of the tasks and adequacy of the audit trail.
  - Validate SMA workforce is adequately sized and manned to accomplish its mission to enforce quality and safety.
  - Implement the MAIB “model for compliance verification”
  - Return to past closed loop discrepancy system.
  - Return to true FOD definition, enforce “clean as you go” program.
  - Ensure no closeout work can be done by a single person alone (e.g., foam spraying).
  - Allow employees to accomplish the duties in their PDs (I).
  - NASA Code Q examination of safety specialist manning and responsibilities at KSC (in relation to USA safety).
Maintenance
FOD Policy

- Action / Issue: USA / NASA Foreign Object Damage (FOD) Prevention Programs Require Evaluation
- Background / Facts:
  - USA program consists of daily debris walk-downs by management, workers "clean as you go," and statistically-based process sampling
  - 23 separate checks of launch pad complex from pre- to post-launch accomplished in varying levels of detail by various organizations
  - USA FOD prevention metrics differentiate "FOD" and "process debris"
    - "FOD" – After job is stamped
    - "Processing Debris" – Before job signoff or end of shift
  - No other NASA contractor uses this category
- Findings:
  - FOD prevention is highly emphasized in USA/NASA daily operations
  - Assessment of responsibility is delineated: S&MA (NASA) responsible for FOD and S&MA (USA) primarily responsible for Process Debris

- Recommendations:
  - Greater NASA involvement in FOD program beyond GMIPs or occasional process sampling may improve program emphasis
  - NASA's role regarding the FOD program should be evaluated for expansion of inspector involvement and expansion of inspections
  - Address "Process Surveillance" of all processes, including FOD prevention
  - Eliminate alternative definitions of FOD
    - Could be interpreted as diminishing significance
  - Eliminate lines that separate NASA and USA quality assurance by authority over FOD prevention
  - Realign FOD fee algorithm to increase FOD impact

Maintenance
FOD Policy

- NASA inspects and assesses FOD failures only after USA has closed a WAD
- "FOD" is an industry standard term – basis for prevention programs and immediately recognized as critical part of prevention
- Commonly expressed opinion: FOD was redefined to accommodate SFOC award fee determination
- FOD and Process Debris are "leader" metrics that are rolled up into the TMK's scoring for inclusion in the SFOC award calculation.
  - First half FY 03 performance assessment: the "good" FOD rate canceled out the moderate Process Debris rate
  - Unique effect of splitting FOD into two metrics
  - Second half FY 02: 24th worst performance in both categories, award fee impact minimal, received highest score ever in roll up
  - FOD found on launch pad is a direct award fee impact
Maintenance Capabilities Analysis

- **Findings (cont'd):**
  - Both Orbiter Operations (OPF) and Integrated Logistics (TPSF) are assessing capabilities against requirements.
  - Presented various options to potential increases in requirements:
    - Work employees longer, augment work force with additional manpower, slip delivery schedule.
  - For TPSF, additional options include:
    - Reactivating Palmetto tile shop to produce test tiles.
    - Augmenting KSC with Palmetto technicans.
  - Both capability assessment efforts in a fledgling state:
    - Represent efforts to communicate workforce constraints and mitigation options to management-levels.

- **Findings:**
  - Work load variations driven by numerous factors:
    - Vehicle age, modifications, mission requirements, etc.
  - One example: OV-103, currently 8 months into J3 OMM:
    - 28 percent growth over original tile replacement projections.
    - 11.5 percent tile growth over original projected man hours.
    - Potential additional tile growth ranges from 7 to 24 percent.
    - From original 82,522 to 111,892 man hours.
  - Second example: TPSF (tile backshop):
    - Currently supporting GV-103 OMM, OV-104 flow.
    - Test tile production (CAIB support) increasing from 47 percent.
    - Mar - May 03: 128 originally projected, 666 now required.

Maintenance Capabilities Analysis

- **Findings:**
  - Ground Operations managers also "plowing new ground" with capability assessments using "equivalent flow" (EF) model:
  - Based on OPF/ET/ORP/Brookings integration of 525,000 man hours.
  - OMM baseline being developed using GV-103:
    - 700,000 man hours estimated.
    - Adjustments made based on OMM/flow context.
  - EF capabilities being applied against launch schedule (manifest) to determine shortfalls:
    - Original FY 03/04 manifest exceeded EF capability by as much as 64%.
    - Managers envision being able to level "peaks" and fill in "valleys.
    - Managers using EF capabilities to develop mitigation plans.
    - "Key question: How flexible can/ will the launch schedule be?"
Other
Fleet Experience – Aging

19-1  Loose Carrier Panel Fasteners
19-2  Programming for Aging Infrastructure
Carrier Panels

- Action / Issue: Determine adequacy of maintenance requirements for carrier panel fasteners
- Background / Facts:
  - Upper and lower access/carerter panels closeout the WLE between the RCC panels and the wing front spar
  - OV-102 has 794 total carrier panels including the OMS pods
  - WLE lower carrier panel utilizes a gap filler referred to as a "horseshoe"
  - OV-102 left wing lower access panels had 27 horsesshoes replaced, 9 HRSI tiles replaced, 8 tiles in the gap filler material, 12 HRSI tile repairs and 7 MRs
  - OV-102 left wing upper access panels had 7 HRSI tiles replaced, 7 HRSI tile repairs and 7 MRs
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Carrier Panels

OV-103-01, WLE Carrier Panel 7L Stumped Tile (1984)

OV-103-04, WLE Loose Carrier Panel 16R (1985)

Carrier Panels

OV-104-21, WLE Carrier Panel 7L Stumped Tile (May 00)

Carrier Panels

Category: Other Significant Finding

- Findings:
  - Carrier panels have a history of having loose fasteners
  - Recommended monitoring plan appears to be inadequate (if it was even implemented)

- Recommendations:
  - Revisit carrier panel loose fastener issue and revised planned maintenance actions

Carrier Panels

- Documentation:
  - Briefing by A. Mirdamadi, "TPS Carrier Panel Fasteners Monitoring Plan", 30 March 1999
  - Briefing by S. Cavannaugh, "OV-102 Wing Leading Edge Carrier Panel", January 1998
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Aging Infrastructure Facilities/Equipment

- **Action / issue:** Assess aging infrastructure, to include planning/programming of sustainment/replacement actions
- **Background / Facts:**
  - Much of NASA infrastructure (facilities/equipment) was built in the Apollo era (1960s); design life was 10 years
  - Relocated/modified numerous times to remain "launch ready"
  - KSC further challenged by accelerated corrosion due to proximity to ocean; acidic SRM exhaust compounds pad-vicinity problems
  - Primary focus on infrastructure deemed critical to immediate mission; many other systems have received only basic attention (at best) and are well past their projected service life
  - Major budget cuts from 1994 led to NASA strategy to absorb most reductions from infrastructure
  - Facility maintenance strategy WRT SSP abruptly changed from "life support until imminent retirement" (1996) to "sustain until 2020"

**Findings:**

  - Example 1: Launch Pads
    - Extensive structural corrosion due to SRM propellant/aerosol contact to ocean
    - Older designs trap corrosive elements despite post-launch washdown
    - Decontaminated walls in HGS Payloader Change Room (temp fixed)
    - Concrete deterioration problems at pad base & blast deflector area
    - Railroad boxcars (36 between LC 39A & B) serve as offices/work centers
  - Severely deteriorated, some with evidence of leaking ceilings
  - Efforts to reverse this deterioration evident in some areas
    - Pad wiring upgrades in Pad Terminal Control Room reflect continuous attention to sustainment critical to launches
    - Later structural additions reflect designs less prone to trap corrosives
    - Boxcar replacement facilities funded, move-in this year (FY 03)

Aging Infrastructure Facilities/Equipment

- **Findings (cont'd):**
  - Example 2: Crawler/Transporter
    - Designed/built for the Apollo program (circa 1968); only two in world
    - Currently have an average of 1,700 miles each
    - Critical for launches, if during hurricane season (to "safe haven" shuttle)
    - Challenges: age, obsolescence, vanishing vendors, small fleet size, uniqueness, highly corrosive environment/outdoor storage, etc.
      - Despite these challenges, CTVs are recognized for their critical role and are well supported (e.g., control room upgrades/laser docking)
      - One notable exception: outdoor storage accelerates corrosion and leads to continual weather discharges (work shop for lightning)
    - Managers track resources expended (cost of mods/partstake) over time via per unit of output (e.g., miles driven or operating hours)
    - In certain cases, analysis/budgeting of support costs based on unit of output can more clearly define cost/benefit tradeoffs

Aging Infrastructure Facilities/Equipment

- **Findings (cont'd):**
  - USA in its 3rd yr using a web-based corrosion info/tracking system ("CorProBasecoat"); adopted from offshore oil industry
    - "Light years" ahead of former paper system, file cabinets w/old files & paper reports, time consuming to prepare, review, & update
    - Using CorPro, engineers annually assess infrastructure, using digital photo documentation, work prioritized based on corrosion severity
    - CorPro also enables forecasting timelines/allocations for corrective actions
      - Valuable tool in prioritizing replacement issues for acceptable actions
    - Ground Systems Working Team (GSWT) assesses/prioritizes infrastructure requirements
      - Considers trade associated with likelihood of failure and consequences
      - Factors in cost savings avoidance
      - Uses Ground Systems Survivability Assessment (GSSA) database

- **Findings:**
  - "The hardest part of our job is getting the funding, the resources, and the operating schedule window to line up"...senior NASA/USA mgs
    - Effective scheduling of preventative/corrective maintenance of ground support systems essential to maximizing windows of opportunity
    - USA’s Ground Systems Support (GSS) established a master planner position in late CY 99
    - Similar position established for horizontal operations in early CY03
    - These two new planners routinely interface w/vertical operations master planner to better align/coordinate activities
    - Overtime hours and work time deadlines/valids have been decreasing with this new focus
    - Another expectation: more infrastructure support will be accomplished based on lining "windows" more efficiently

Aging Infrastructure Facilities/Equipment

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**Aging Infrastructure Facilities/Equipment**

**Findings (cont’d):**

- **MSFC/ Michoud Assembly Facility (GOCC-goit owned contractor operated)**
  - Some facilities date to 1940s, add-ons for Apollo (60s) and SSP (70s)
  - Advantages (over KSC): smaller operation, more single-mission focused, fewer "bulls to juggle," much less corrosive environment
  - KSC: 15 yr Strategic Plan prioritizereme in "big picture" context
  - Developed in 97; ongoing updates; disciplined, systematic approach
  - Also have a comprehensive 15-yr Equipment Strategic Plan
  - Successes:
    - CoF funding increased by 33% (FY 03 vs 02), $100M to $130M
    - Repair of 45-acre roof on Main Mtg Bldg in 240 days
    - Increased 15yr engineering system, 4.1yr segments
  - Despite being challenged by old infrastructure, MFAs approach has typically secured needed funding

**Aging Infrastructure Facilities/Equipment**

**Findings (cont’d):**

- The NASA "big picture"
  - >2,600 buildings, >3,000 other major structures, avg age nearing 40 yrs
  - $31B Replacement Value (CRV), avg NASA CRV 40% > DoD
  - Reflections unique nature of facilities (e.g., MBR, launch pads)
  - NASA-wide infrastructure assessment conducted in FY 02
    - Backlog of Maintenance and Repair (BMR) not National/ available, subject to "spin," difficult to mill up
    - New unique "yardstick" via Defended Maintenance (DM)
    - >5B DM NASA-wides
  - 100% BMR estimate, which did not consider all facilities
  - NASA-wide Infrastructure Industry rule of thumb: 2.4% annual funding
  - NASA playing catch up based on years of underfunding
  - Uniqueness/small # of facilities also drive a "must fix" approach
  - Code JX working to apply DM database to planning/programming

**Aging Infrastructure Facilities/Equipment**

**Findings (cont’d):**

- NASA "big picture" continued
  - Code JX has adopted DoD’s Facility Sustainment Model (FSM)
    - Believing model for NASA use
  - FSM requires $33M annual facility maintenance funding to arrest deterioration
    - FY 05: $24M (50% of goals)
    - FY 02: $170M (42% of planned)
  - Facility Reutilization Rate (FRR) measures how often a facility will be replaced/reutilized based on investment funding
    - 60% FRR target (60 yrs, industry standard in 5 yrs, current NASA FRR > 100 yrs (delayed from 2007 yrs)
    - Estimated cost for NASA to reach 60 yrs: $10Bn
  - Improvement also possible by reducing Infrastructure
  - NASA addressing this via DAFOS assessments & tools such as DAFOSIR

**Aging Infrastructure Facilities/Equipment**

**Findings (cont’d):**

- Stennis Space Center (SSC)
  - Built as part of Apollo ramp-up (mid-60s)
  - Primary mission: liquid fueled rocket engine testing
    - Every shuttle engine tested after mod/overhaul
    - Three test stands: "national assets" - A1, A2, B12
    - Only A1 capable of testing megasting
    - A1 to be mothballed in FY 03 (infrastructure reduction)
  - Remaining test stands deemed adequate
    - Known risks do not include gimbal testing
  - Pattern to facilities (aka Plant 42) leased from AF
    - Facilities/equipment generally in good condition due to environment
  - Degradation (primarily equipment) due primarily to decreased activity/use

**Aging Infrastructure Facilities/Equipment**

**Findings (cont’d):**

- A second uniform "yardstick" Facility Condition Index (FCI)
  - A=5 scale: 5 is excellent, 1 is bad
  - Average ratings based on FY 02 NASA-wide assessment:
    - NASA: 3.6 - Code B: 3.5 - SSC: 3.6
    - KSC: 3.3 - MSFC: 3.9 - SSC: 3.1
  - KSC rating reflects large number of assets (>60%) dedicated to SSP
  - SSC rating skewed by high 5% value, condition of test stands relative to overall center value; stands are 37% of SSC CRV w/FCI of 2.2, w/ test stands, SSC is 3.6
  - Assessments "peel back" to individual areas: structure/roof/exteriors/ interiors/trusses/ACA/Utilities/equipment
  - NASA goal: improve average to 4.2 by FY 09, requires $310M/yr

**Aging Infrastructure Facilities/Equipment**

**Findings (cont’d):**

- NASA road ahead
  - Identify/track of excess infrastructure
  - Make better use of une-ill utilized facilities through consolidations
  - Sustain remaining infrastructure by:
    - Reducing backlog of maintenance and repair
    - Bringing revitalization rate down from 100+ yrs
  - Advocating for "repair by replacement" where smart
  - Successfully advocating/maintaining funding to support all of above

**Conclusions / Recommendations:**

- Strategic level assessment/planning by Code JX on the right track
  - Provides a structured approach to assess and prioritize requirements
  - Based on recognition that past assessments have not presented an accurate picture of NASA-wide requirements prioritization
  - 15-yr Strategic Plans at MAF are worthy of benchmarking across NASA
  - Allow a long-range view (beyond 5-yr POP) for proper prioritization of both facilities and equipment
Aging Infrastructure
Facilities/Equipment

- Recommendations:
  - KSC should continue its initiative for improved scheduling integration: the
    recent addition of master planners for horizontal ops & GSS to interface
    with vertical ops is a great move in this direction
  - KSC GSS management should consider tracking support costs relative to unit
    of output (i.e. over time) in selected areas; this can assist in tradeoff
    decisions on funding model upgrades vs. repairs.
  - Given the amount of aging infrastructure/equipment, this can be a valuable
    decision tool.
  - KSC should continue efforts to improve management distribution of
    workload and costs thru systems such as CorPro/RealCost.
  - Explore application to non-corrosion related infrastructure.
  - KSC should perform cost/benefit tradeoff analysis of constructing add'l
    shelters for equipment (not limited to C-17). This will reduce weather
    deterioration resulting maintenance and weather-related work stoppages.
  - KSC should examine current launch pad maintenance practices and make
    every effort to further reduce/eliminate zinc fallout.
  - Other centers should benchmark KAF's 15-year infrastructure and
    equipment strategic plans, a "long view" of these critical issues is essential.

Aging Infrastructure
Managing Using CorPro Software

Manages all corrosion data for status tracking and
programming of maintenance.

Aging Infrastructure
Severe Corrosion - Pad 39A

Aging Infrastructure
Corrosion/Boxcars at Pad 39A

Aging Infrastructure
VAB Deterioration

- Roof
- Sidings
- Doors

Aging Equipment
C/T and NLP

Mobile Launch Platform
Aging Infrastructure
CRV/BRMAR/DM/FCI by Enterprise/Center

Aging Infrastructure
Facility Condition Index (FCI) – Code M = 3.5

Aging Infrastructure
Facilities Maintenance and BMAR

Aging Infrastructure
Facility Revitalization Rate - Just Over 100 Years
Other
Maintenance

20-1 Engineering Orders
 Maintenance Engineering Orders

- **Action/Issue:** Backlog of unincorporated Engineering Orders (UEO) is significant and may impact the quality and timeliness of maintenance
- **Background:**
  - Last 5 AGAP reports document a large and growing number of UEOs (over 1500 with > 10 changes each, now 1400 with removed from schedule)
  - NNBEE referenced using Navy's zero level as a baseline
- **Facts:**
  - Observed examples of UEOs in shop and OPF
    - Observed the impact and difficulties of navigating EO with multiple unincorporated changes and potential for human error
    - NASA built a noting plan to incorporate the most important changes to drawings for orbiter on basis of highest use and complexity (2002-2004)
- **Recommendations:**
  - Draft a plan to finish incorporating the >10 UEOs

Aerospace Safety Advisory Panel, 2002... report excerpt:

"Previously, the Panel has been concerned with the large number of orbiter drawings that are out of date. Many EO changes have not been incorporated into the drawings. Although they are noted on the drawings, engineers must refer to additional paperwork to understand the state of the hardware systems. Over 1,600 drawings have more than 10 unincorporated EOs. The orbiter program will update and incorporate all EOs on 59 of the most frequently used drawings by the end of 2003. Also during the year as an effort to address the 589 drawings referenced most frequently after those 59 will begin. The remaining drawings will be updated as opportunity permits. Orbiter program management has committed to maintaining the upgraded drawings at no more than 10 unincorporated EOs. The orbiter program is now reviewing the possibility of identifying the safety-critical drawings that should always be kept current.

Recommendation 02-8:

Identify drawings that are critical to flight safety, update them to include all EOs, and keep them current."
Other
Launch – Ascent

21-1  Day of Launch Assets, Hardware Security, and Scenarios
21-2  SRB Bolt Catchers
21-3  Separation Bolt Certification
21-4  RSRM Flex Boot Tear
21-5  STS-107 Impact Analysis
21-6  STS-107 Ascent Debris (Radar & Imaging)
21-7  Hold-Down Cable Anomaly
Willful Damage
All Areas

- Action/Issue: Potential for willful damage
- Background/Facts:
  - Dry-of-Launch Assets included:
    - Pilots
    - Helicopters
    - Sea surveillance
    - Ground security
    - Sensors
    - “Tightest security ever... brief to NSC”

Hardware Security

- Background/Facts:
  - Panel and door close-outs
    - Multiple technicians
    - Multiple contract quality inspectors
    - Multiple government inspectors
  - RCC panels
  - Inside wing

“Willful damage” scenarios

- Background/Facts:
  - Examining via testing (outside agencies involved)
  - HOWEVER... to be credible, each must still pass “tests”
    - Telemetry (digital, voice)
    - Imagery (still, video, telescopic)
    - Thermodynamics
    - Aerodynamics
    - Orbital shedding, ground evidence
    - Documentation
    - And – grounded in shuttle systems facts

- Findings:
  - Thus far, none meets the tests to be credible
  - FBI testing and chemical/metallurgical evidence do not support willful damage

- Recommendations:
  - Continue high level of diligence to prevent willful damage
**Maintenance Bolt Catcher**

**Action/Issue:** Did a malfunction of the SRB forward Bolt Catcher contribute to the accident chain of events?

**Background/Facts:**
- Function: Catch fired separation bolts attaching SRBs to ET
  - Upper catchers attached to ET, lower attached to SRB, different design
  - Good example of SIAT (99) documented concern with "fly what you test, test what you fly"
- SUMMA and Harris manufacture, subKtr, USA serial #
  - Pulled from supply to install on ET, coated with (SLA) additive which resulted in improper discard
  - Serial # discrepancy between USA and MAE serial # on STS-107

**Findings:**
- Dynamic test #2 measured 44KIPs in Summa serial #50 dome
- Stress test #3 of catcher failed at weld at 44KIPs… engineering analysis expected bolt failure at 68,000lb
- Same failure point as 1979 certification test
- Implies 0.956 safety margin
- Additional tests requested
- X-Ray film of #50 showed poor quality film and strong evidence of substandard weld, would not have been certified today STS-107, Summa catcher #1 installed on left SRB/ET
- X-Ray film failed in quality as well as substandard weld

---

**Bolt Catcher**

**Background/Facts:**
- Bolt Catcher never qualified as flown… 7/9/80 tests
  - Attachment to ET qualified with through-holes (vice inserts)
  - SLA 561 not applied on test articles
  - Reduced resistance aluminum honeycomb not tested
  - System changes certified by "analytical and similarity"
  - In-flight photograph of STS 107 Bolt Catcher black and unusable
  - Radar image at 126 seconds point originally considered normal

**Findings:**
- Tests run 7/18/07 – 8/7/07 of stator and stator - stator environments and safety margin
- Tests designed to verify engineering profile of system performance as certified including axial configuration
  - 18 tests completed… 4 bolts fired into instrumented catcher, seven stress tests of catcher to failure

---

**Bolt Catcher**

**Findings:**
- STS-107 launch radar data comparison with bolt catcher radar cross section (RCS) complete
  - Event #3 at 126 second similar in size to bolt catcher RCS
  - Lack of photographic evidence means event #3 cannot be ruled out as a possible bolt catcher or fragment.

**Group Recommendations:**
- Certification by "analytical and similarity" flawed… how many other bolt catchers on SSP?
  - Remove all Bolt Catchers from service
  - Redesign system to assure 1.4 safety margin at a minimum
Maintenance
Separation Bolt Certification

**Action / Issue:** Separation bolts manufactured by Pacific-Scientific were not adequately ND'd before flight on STS 107

**Background / Facts:**
- USA replaced Hi-Shiv as the prime contractor for separation bolts in May 2000. Certification of new bolts may have been done without adequate NDI (magnetic particle) of the internal bore

**Findings:**
- P-S used Pacific Magnetic and Penetrant for NDI verification
- P-S/PMP used same NDI specifications as Hi-Shiv
- First lot (Lot AA) used on STS 107 and installed on STS 114
- All NDI results were approved and certified by PMS, USA, and DCMA
- 2nd lot (AAP) magnetic particle inspection evaluated by DCMA NDI expert
- Determined process inadequate WRT analysis of Magnetic Part. Insp.
- ASTM E 1444-01, par. 5.7.3 stipulates use of a borescope

**Findings (con't):**
- USA had verbally authorized PMP to deviate from the purchase order specification since borescope was not available
- USA and DCMA NDI experts disagree over test sufficiency
- USA built a Defect Standard Bolt with known flaws to evaluate process
  - "Initial assessment of PMP's inspection procedure by USA NDE confirms procedure meets engineering requirements imposed but could be improved"... USA briefing to CAIB
- USA impounded existing supply of 1st lot: dedicated to test only
- This situation is not a contributor to the STS-107 mishap

**Recommendations:**
- Use more stringent inspection criteria IAW ASTM E 1444, par. 5.7.3. Restricted Area Examination with borescope or new method that can adequately identify flaws in the ID
Ascent Debris Strike
Other

- Action / Issue: 57-inch tear in the flex boot on the right RSRM adjacent to the inner boot ring—first time observation

- Background / Facts:
  - Flex boot is key to allowing reuse of the RSRM
  - Separation did not result in violation of flex boot thermal protection—still not sure of the cause—might have been water impact

- Findings:
  - None at this time

- Group Recommendations:
  - Issue closed per RSRM Fault Tree closeout on 9 Apr 03
Ascent Impact Analysis
(includes Crater)

- Action / Issue:
  - The impact damage analysis process did not accurately predict the damage sustained by OV-102 during the ascent of STS-107

- Background / Facts (Impact Analysis Process):
  - Crater is a term used in impact analysis
  - "Impact Analysis" includes Crater, thermal, & stress analyses
  - For STS-107, the impact analysis was performed using the image analysis team's assessment of debris size and location
  -Crater program predicted severe damage to several tiles
  - Thermal and stress analyses predicted localized heating but safe return of orbiter
  - Boeing's Debris Assessment Team recently experienced a transition from Huntington Beach to Houston

---

Ascent Impact Analysis
(includes Crater)

- Background / Facts (Crater):
  - Crater is a semi-empirical/semi-theoretical set of equations that results in a life damage prediction for Li-900 tiles
  - Crater is only model used by NASA to predict impact damage to tiles
  - Crater is conservative and credits worst case damage
  - Crater originally designed for "in family" (small < 3 in) hits
  - Crater is appropriately named; accounts for only for cratering (no other damage mechanisms considered)
  - Never intended to be used for large projectiles (STS-107 analysis)
  - Extrapolation to higher energy debris never validated through testing
  - Crater predicted severe damage to several tiles for STS-107
  - Crater's capabilities are limited by test data used to verify the model
  - Most probable cause of Columbia accident has been identified as impact damage to RCC panels
  - Revised photo analysis
  - Analysis of onboard instrumentation
  - Forensic

---

Ascent Impact Analysis
(includes Crater)

- Findings (Impact Analysis Process):
  - Basic type of analyses performed at Boeing-Huntington Beach (pre-transition) and Boeing-Houston (for STS-107) appear to have been the same
  - Boeing-HB and Boeing Houston differ in their assessment of the effectiveness of the training program
    - Boeing-HB training was provided by HB personnel
    - Boeing-HB training included training quality & quantity sufficient
    - Boeing-HB training was adequate to meet the needs of the training program
    - Boeing-Houston team believes training quality & quantity sufficient
  - Boeing Houston team states OUT occurred in Houston, independent of HB training to understand:
    - Supporting documentation
    - Crater equation development
    - V' threshold development
    - Sensitivity studies reported to have been conducted prior to STS-107 final analysis release

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Ascent Impact Analysis
(includes Crater)

- Findings (Impact Analysis Process):
  - Impact analysis uses an iterative, multidisciplinary (transport, impact, Crater, thermal, stress) team-based process
  - STS-107 analysis appears to have been done in the same manner however, without enough feedback between analysis components
  - Thermal analysis may have had minor errors due to communications issues with the Crater analysis hand-off

---

Ascent Impact Analysis
(includes Crater)

- Findings (Crater):
  - Crater's use on STS-107 was far outside it's verified limits of applicability
  - Crater limitations:
    - Only for Li-900 tiles
    - Does not account for special geometry present on some tiles
    - Valid for ascent impact velocities only
    - Immateriality impacts not part of its methodology
    - Valid for a limited set of impactor materials
    - Impactor shapes limited to cylinder, rectangular block, or sphere
    - For rectangular block impactors, predicts damage for "edge" orientation only
    - Does not include effects of crossing tile boundaries in large impacts
    - Need to define more stringent limits to Crater's usage when tile depth reaches a defined % of total tile thickness

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Report Volume V October 2003
Ascent Impact Analysis (includes Crater)

- **Findings (Crater):**
  - Crater works well within its established limits
  - In the experimental space in which Crater was developed (test projectiles up to 3 in.), it provides a reasonable solution
  - Extrapolating beyond the limits of Crater may be performed with:
    - Interpretation based on experience
    - An understanding that the accuracy of predictions will be reduced
  - Crater does not capture "non-cratering" effects on tile or substructural response
  - Crater is not a "turn-key" code
  - Effective use of Crater assumes users have knowledge of model's development and experience in interpreting results
  - Crater has been underutilized in developing acceptable debris/criteria for "in Family" hits

- **Recommendations (Impact Analysis Process):**
  - Boeing should not view the process for knowledge capture as "complete," despite the completion of the transition period
  - They should build on previous efforts to develop a systematic and comprehensive training process to ensure ongoing proficiency in critical tasks
  - Boeing/NASA should conduct an in-depth training curriculum for Boeing-Houston to ensure proper understanding and interpretation of impact damage analysis models and procedures
  - Fine & open communication between Boeing-Houston and Boeing-HB should be encouraged and financially supported until it is agreed that a full and proper transition is complete

Ascent Impact Analysis (includes Crater)

- **Findings (Crater):**
  - For STS-107, the Crater model predicted severe damage to several tiles
  - Crater results were interpreted using potentially un-conservative assumptions based upon inherent conservatism of model
  - Extent of tile damage assumed to stop at lift-off has been identified

- **Recommendations (Impact Analysis Process):**
  - Boeing, under NASA supervision, should review training matrices for transitioned personnel to verify individuals meet established requirements
  - Upon completing the review, action plans should be developed to remediate those not meeting set job criteria.
    - Boeing should risk manage the remediation process, not only on a group/technology area level, but also on an individual employee level.
    - Particular attention should be given to new hires with low flight experience and areas with several inexperienced personnel.
  - Boeing should employ HB initiatives to remediate transitioned personnel failing to meet established job criteria
  - Affected employee's time should be dedicated to the programmed remediation

Ascent Impact Analysis (includes Crater)

- **Recommendations (Impact Analysis Process):**
  - NASA/USA/Boeing should continue to develop a more robust, physics-based model to analyze impact damage to tile and RCC
  - Development should take advantage of expertise from all available resources
  - Boeing should work to develop a user's manual for thermal and stress analysis associated with impacts
  - Boeing should continue to encourage communication between Houston and Huntington Beach technical communities in the future

Ascent Impact Analysis (includes Crater)
Ascent Impact Analysis
(includes Crater)

• Documentation
  - CAIB Request for Information, "ET Debris Impact Records," B1-0000013
  - CAIB Request for Information, "Background Info on the CRATER Model," B1-0000063
  - CAIB Request for Information, "CRATER Model Technical Discussions," B1-000186

Ascent Impact Analysis
(includes Crater)

Orbiter Impact Assessment Overview

Damage Results from Crater Equations Show Significant Tilt Damage

- "Crater," indicates that multiple sizes would be taken down to semi-damaged layer.
- Tilt is expected to be conservative due to large number of unknowns.
- Crater reports damage for test conditions that show no damage.

Experimental Basis for Crater
- NASA, Boeing, and Texas A&M tests performed 1978-1982

Ascent Impact Analysis
(includes Crater)

Theoretical Basis for Crater
- Boeing penetration equation developed for Apollo program for meteoroid analysis was adapted to predict projectile penetration into TPS tiles

\[ p = \frac{0.0195(L/d)^{0.56} \left(\frac{d}{\rho_p}\right)^{0.2} \left(V - V^t\right)^{0.1}}{(S_c)^{0.4} \left(\rho_f\right)^{0.6}} \]

Where:
- \( p \) = penetration depth
- \( L \) = projectile length
- \( d \) = projectile diameter
- \( \rho_p \) = projectile density
- \( V \) = normal component of impact velocity = \( V \sin \theta \)
- \( V^t \) = threshold normal velocity to penetrate tile coating
- \( S_c \) = tile compressive strength
- \( \rho_f \) = tile density
- 0.0195 = empirical constant
Ascent Debris

- **Action / Issue:** Review radar and optics results for evidence of debris during ascent.
- **Background / Facts:**
  - STS-107 was tracked during ascent by Eastern Range land-based C-band radar and mass optics.
  - Data was examined to identify any previously undetected debris.
  - No radars detected debris prior to SRB separation.
  - Only the Cocoa Beach Distant Object Attitude Measurement System (CB DOAMS) optical telescope observed debris around 81 seconds.  
  - 81.66 sec: single object between Orbiter nose cone and ET 1st detected, appeared white.
  - 81.82 sec: struck under Orbiter's left wing, disintegrates into a cloud of orange-colored debris.

### Ascent Debris Radar 0.14 Results

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<tr>
<th>CATALOG</th>
<th>PIECE NUMBER</th>
<th>FIRST APPEARANCE</th>
<th>LAST APPEARANCE</th>
<th>MAX RCS (dBsm)</th>
<th>RANGE SEPARATION RATE (m/s)</th>
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### Ascent Debris Radar 0.14 Results (Continued)

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*The RCS and range separation rate of these pieces cannot be determined due to the low level of signal return. RCS is estimated to be within 0 to 3 dB of the Minimum Detectable RCS.

** These events have been determined to be due to plume effects.

### Ascent Debris Radar 28.14 Results

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*The RCS and range separation rate of these pieces cannot be determined due to the low level of signal return. RCS is estimated to be within 0 to 3 dB of the Minimum Detectable RCS.

### Ascent Debris

- **Findings:**
  - Radar detected debris after T=150 seconds.
  - Debris could not be identified.
  - Radar returns similar to past STS missions.
  - CB DOAMS observed debris between Orbiter and ET at 81.66 seconds.

- **Recommendations:**
  - Issue should be closed.
Ascent Debris

• Documentation:
Maintenance
Hold Down Cable Anomaly

- **Action / Issue:** Could orbiter MECs/cabling failure to the hold down post (HDP) pyrotechnics and ET vent arm system (ETVAS) be catastrophic?
- **Background / Facts:**
  - PIA #0007 stated that STS 112 had a failure in the system that controls firing of the initiators in each SRB restraint nut.
  - Redundancy in each Master Events Controller (MEC)
  - MEC1 feeds A system, MEC2 feeds B system
  - Each nut has two initiators, one on A system, one on B
  - Signal sent by MECs to nut to fire and ETVAS to retract
  - Either MEC will operate system in event of failure in the other
  - During STS-112 the Ground Launch Sequencer (GLS) issued "Cut Off" after 3 seconds
    - Post-launch review indicated that system A-HDP and ETVAS Pyrotechnic Initiator Controllers (PICs) did not discharge

Maintenance
Hold Down Cable Anomaly

- **Findings:**
  - Pyro systems A and B are independent and redundant
  - The HDP and ETVAS systems receive Fire commands at T-0
    - Fire 1 and Fire 2 commands are sent as a nearly simultaneous event
    - Each redundant pyro device is initiated by a dedicated PIC
    - 16 separate PICs for "A" and "B" HDP devices and four separate PICs for "A" and "B" ETVAS devices
  - The PIC design requires 3 separate commands to detonate its NASA Standard Initiator (NSI)
    - A1M—Activates the PIC’s power supply and charges capacitor bank
      - Fire1—Activates a switching transistor controlling the PIC output return and enables the Fire2
  - Fire2—Activates a switching transistor controlling the PIC output
  - ETVAS pyro Fire commands are branched from the HDP Fire commands
  - HDP "A" PIC and ETVAS "A" PIC failed to discharge

Maintenance
Hold Down Cable Anomaly

- **Findings:**
  - Extensive analysis and study was initiated immediately
  - Approx. 25 different potential fault chains were considered as source of A system failure
  - Definite cause never determined, considered intermittent
  - Most probable cause: the fire 1 command wasn’t transmitted properly from MEC 1 to PIC Rack 6743 in the MLP
  - Focus of command path anomaly is on T-0 electrical interface
    - Not cleared during investigation since normal function (T-0 separation) destroyed evidence
  - Inspection has detected wear and contamination at interface

Maintenance
Hold Down Cable Anomaly

- **Findings:**
  - STS-112 investigation recommendations implemented:
    - All T-0 Ground Cables have been replaced after every flight
    - T-0 Interface to PIC rack cable in redesign. ETIC July 03
      - Over 1 T-0 Ground cable and two Kypor
    - All Orbiter T-0 Connector Savers have been replaced
    - Pyro connectors prescreened with pin retention test
  - Connector saver mates will be verified using VideoScope

- **Recommendations:**
  - Inquiry released for failure potential on this CRIT IR system
  - Specifically, what is chance of a concurrent failure of a MEC/cable and one or more initiators? What would result? Can NASA redesign system to add cable from each system to every initiator so a signal system failure would not disable half of the initiators?
Maintenance
Hold Down Cable Anomaly
FD2 – On-Orbit Object

- Action / Issue: Determine on-orbit object detected by ground radar during post-flight data review
- Background / Facts:
  - While on orbit, 3,180 separate radar or optical observations of Columbia were collected
  - Collection sites included: Eglin AFB, Beale AFB, Navy Space Surveillance, Cape Cod, Maui, and Kirtland AFB
  - Each observation was individually examined after the accident
  - 1st Space Control Squadron and AFSPC Space Analysis Center personnel conducted detailed analysis
  - Post-flight processing discovered a small object in shuttle orbit
    - Object referred to by International Designator 2003-003B

FD2 – On-Orbit Object

- Event Timeline:
  - Jan 17, 1442Z: Shuttle reorriented
    - Moved from tail-first to right wing-first orientation
  - Jan 17, 1517Z: Shuttle reorriented
    - Returned to tail-first orientation
  - Jan 17, 1600-1615Z: Object 2003-003B separates
  - Jan 17, 1857Z: First confirmed sensor track
  - Jan 19, 2148Z: Last confirmed sensor track
  - Jan 20, 0145-0445Z: Object 2003-003B decays

FD2 – On-Orbit Object

- Background / Facts:
  - On-orbit object 2003-003B detected by Cape Cod PAVE PAWS radar during passes on 3 days before de-orbiting
    - Day 1 Track: -18 to -4 dBsm
    - Day 2 Track: -15 to -2 dBsm
    - Day 3 Track: -13 to -1.75 dBsm
  - Object tumble rate increased with time
  - RCS varies from ~0.1 to ~0.7 m²

FD2 – On-Orbit Object

- Background / Facts:
  - Radar Cross-Section (RCS): combined with ballistics results used to determine potential FD2 object
    - Potential candidate orbiter parts must match both RCS and ballistics as a minimum
    - AFRF conducted RCS measurements of 26 orbiter parts to compare to on-orbit signature and 4 RCC pieces from STS-107 RH debris
    - US Space Command determined ballistics coefficient of on-orbit object and all parts measured for RCS signature
    - Ballistics coefficient = (Drag Coefficient * Area) / Mass
    - Area/Mass ratio for on-orbit object determined to be 0.1 meters² / kg
FD2 – On-Orbit Object

- **Background / Facts:**
  - Obtained RCS measurements for the following RH parts from OV-102 debris:
    - Part 51311, 8' x 13' RCC fragment with lip
    - Part 37736, curved RCC fragment with no lip
    - Part 2016, 8' x 11' RCC flat acreage
    - Part 51313, T-seal fragment at panel 8/9

FD2 – On-Orbit Object

- **Background / Facts:**
  - Parts that matched both RCS signature and ballistics:
    - RCC panel acreage piece if approximately 100 to 150 inch²
    - Parts rejected due to RCS signature, ballistics or both include:
      - 14 blanket-type insulators or cloth-like material
      - 5 outer panel panels with and without honeycomb
      - 4 RSI tiles
      - 1 RCC panel with all metallic hardware
      - 1 upper carrier panel

FD2 – On-Orbit Object

- **RCC T-Seat Measured for RCS Signature**

FD2 – On-Orbit Object

- **RCC T-Seat RCS Results**

FD2 – On-Orbit Object

- **WLE Spanner Beam Insulator Measured for RCS Signature**

FD2 – On-Orbit Object

- **WLE Spanner Beam Insulator RCS Results**
If any part of the upper left side 8/9 or 9/10 T-seal is recovered from STS-107 and the piece falls within the middle of the T-seal or flange (as shown in red), the upper T-seal could then be eliminated from an RCS perspective.
FD2 - On-Orbit Object
VHF RCS Data From Altair Radar

- Background / Facts:
  - A "Corrected" fragment of VHF RCS data was observed from FD2 object on-orbit from the Altair radar
    - Fidelity of this data set estimated by MIT Lincoln Laboratory to be ± 3 dB.
  - AFRL tested V/HH co-polarized RCS of 4 RCC debris components (T-seals and panel acreage) at VHF (158 MHz) with the following results:
    - Cannot eliminate the T-Seal, either whole or fragment
    - Cannot eliminate or exclude RCC panel acreage, especially if the piece has an edge or corner that produces a resonance effect.

FD2 - On-Orbit Object
MIT Lincoln Lab Results

Flat Spin Example
(Propeller Blade Concept)

- Objective: Experimental evaluation of fragment's behavior in free flight
  - Obtain panel 15m x 9m x 2m
  - 316LN aluminum plate with 2m holes on the back
  - Free-molecular flow regime
  - May be just enough restoring moment to keep piece forward
  - Panel provides rolling moment
  - Experimental atmosphere
  - Ballistic coefficient ~10 km/s
  - Panel's cooling
  - Initial 95% to 99% density after 2 days
  - Initial 95% to 99% density after 2 days

FD2 - On-Orbit Object
MIT Lincoln Lab Results for ½ T-Seal

- Static Pattern: Half T-seal 3 in 1
  - Data: Eight Day 19 HH Polarization
  - RCS Measurements

FD2 - On-Orbit Object
MIT Lincoln Lab Results

Spin Up Motion Model
Shuttle Fragment Frequency Points Computed From RCS Data

- Frequency Spin Up Model
  - 1.5 Mph to 0 (measured)
  - Data: 11.97 (950 MHz)
  - 11.97 (950 MHz)
  - 11.97 (950 MHz)
  - 11.97 (950 MHz)
  - Consistent with T-Seal Design

FD2 - On-Orbit Object

- Findings:
  - 41 items screened for either ballistics or RCS testing by NASA, AFSPC, and AFRL
  - Only RCC T-Seal/T-Seal Fragment, RCC panel fragment in the 1/3 inch thick region (lower portion of panel 8 and 9) or a spinner beam insulator could not be excluded based on RCS and ballistics results
  - Qualitative match made between history of radar RCS measurements and RCS simulated for spinning ½ T-seal by MIT Lincoln Laboratory

- Recommendations:
  - Continuously evaluate potential on-orbit object as debris reconstruction efforts progress
FD2 – On-Orbit Object

- Documentation:
  - Briefing by G.H. Stokes from MIT Lincoln Laboratory, "Columbia Fragment Analysis Study Results", 23 May 03
  - Multiple briefings from Dr. Brian Kent, AFRU/SN
  - Briefing from HQ AFSPC/XPY, 18 April 2003
Organization Production

23-1  SSP Centralization/Decentralization
23-5  Contract Management Culture
23-6  CoFR Process Integrity
Production-Organization
Centralization/Decentralization in SSP

- **Action / Issue:** Organizational Characteristics, Policies, & Practices
- **Background / Facts:**
  - Centralized and formal communications, decision-making, and risk management to cope with "tight coupling" linked to the numerous events associated with "normal operations" to provide for immediate responses (e.g., FRS, COFR, etc.).
  - Decentralized and more informal communications, decision-making, and risk management to provide for deliberate analysis to handle unplanned "interactive complexity" of failures by those closest to subsystems (e.g., MMT, MER, etc.).
  - Scheduling demands, workload, staffing shortages, experience, performance incentives, etc. increase the opportunity for tighter coupling and additional interactive complexity for both normal and emergency operations.

Centralization/Decentralization in SSP: Pre- vs. Post- Launch Comparison

- **Pre-Launch:**
  - Centralized Decision Making
  - Defined GoD (Roles & Actions)
  - Formalized Mission Planning
  - Problem Resolution, & SOF Determination
  - Theme: "Prove There Is Not A SOF Problem"
  - NASA Space Centers Visibly Interacting
  - Interactive Complexity Due To Geographic Dislocation & Component Integration Process
  - Tight Coupling Due to Mission Schedule & On-Orbit Operations, # CRIT 1 Hazards & Lack of Redundant Systems

- **Post-Launch:**
  - Centralized Decision Making
  - Delegated Responsibilities
  - Less Formal Mission Monitoring, Anomaly Investigation, & SOF Determination
  - Theme: "Prove There Is A SOF Problem"
  - ISS Primary w/Minimal Outside Center Input
  - Greater Interactive Complexity Due To Orbital Technologies & Space Environment
  - Increased Tight Coupling Due to Real-Time OOC & Little On-Orbit Flexibility, # CRIT 1 Hazards & Lack of Redundant Systems
Organization-Production: SSP Contracting Culture

- **Action / Issue**: Evolution of NASA SSP culture from engineering to one dominated by contract management.
- **Background / Facts**: Transition to SFOC & Primary Contractors has altered the balance of SSP engineering efforts from NASA to contractors.
- **Findings**:
  - SSP engineering personnel shortages have led to reduced oversight of contractor activities, and increased use of “insight” within them.
  - Planned SLP extension and an aging shuttle require added attention to analyze operational stress effects, identify new hazards, etc.
  - Potential risks for reduced engineering awareness to identify problem areas as well as engineering capability to effectively address them.
  - NASA SSP engineering and scientific oversight is necessary to ensure aging aircraft issues are monitored, studied, and acted on.

Automation-Contracting Analogy

- **Reasons for Implementation of Automation in Aircraft**
  - Reduce Pilot Workload to Cope w/Advanced Technology
  - Shift Pilot Primary Focus to Mission vs. A/C Operation
  - Decrease Potential for Pilot Errors
- **Actual Outcomes**
  - Shift from Psychomotor to Primarily Cognitive Workload
  - Causes Similar Errors; Generated New Types

Organization-Production: SSP Contracting Culture

- **Effects of Automation**
  - Increased Systems Monitoring
  - Automation
  - Complacency
  - Loss/Erosion of Situational Awareness
  - Selective Signal Display Filtering
  - Eroded Pilot Skills
- **Effects of Contracting**
  - Increased Contract Monitoring
  - Contract Complacency
  - Loss/Erosion of Program Awareness
  - Selective Signal Display Filtering
  - Eroded Engineer Skills

- **Reasons for Instituting SFOC & Other Contracts**
  - Reduce NASA SSP Workload to Cope w/Budget Constraints
  - Shift SSP Primary Focus to Operations vs. R & D effort
  - Increase Efficiency, Maintain Safety
- **Actual Outcomes**
  - Shift from Engineer Oversight to Contract Manager Insight
  - Some Efficiencies; May have Impacted Safety

- **Recommendations**:
  - NASA must develop a capacity to provide oversight, not only for SMa, but also oversight on the engineering level for each critical technology area.
  - NASA must acquire and develop an engineering staff and provide for requisite training to support both oversight roles.

**Action/Issue:**
Pre-Launch Factors May Impact COFR Process Effectiveness

**Background/Facts:** Reason's "Swiss Cheese" Model is used to categorize/or organize latent conditions of failed or absent defenses that "set the stage" for active failures which lead to incidents; it can also be used for examining those factors affecting decision-making.

**Findings:** SSP COFR is considered a rigorous, systematic process leading to accurate SOF launch decisions. It is perceived as being shielded from outside factors, yet if an organization, supervisor, or member is influenced by external factors, it can be contended the process can miss signals of absent/failed defenses, accept perceived minor deviations, or permit margin of safety reductions.

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The way to manage this risk:
Safety of Flight Issue (TPS Damage from Bipod Strike)

Is to quantify and manage this risk:

- In-Flight Anomalies (Bipod Separation)
- Out of Family/In-Experience Events (Foam Shelling)
- Failed or Absent Defenses
- Unobserved Events (Undetected Voids)

Potential for COFR Process Defense Breaches

- Recommendations:
  - NASA should examine potential pre-launch factors that can influence FRRs and the subsequent COFR process to ensure external factors do not weigh-in on SOF decisions.
  - NASA should ensure potential SOF information is actively sought and acted upon, not filtered and ignored due to pressure, complacency, or norms.
Organization-Fleet Experience: SSP as a High Reliability Organization

- **Action / Issue:** The SSP needs to more closely align itself as an HRO
- **Background / Facts:** Organizations that have less than their "fair share" of failures (e.g., nuclear submarines, petrochemical plants, etc.) despite:
  - managing complex & demanding technologies
  - meeting peak requirements & time pressures
  - routinely handling significant risks & hazards
  - executing dynamic/intensely interactive tasks are termed High Reliability Organizations (HROs). They exhibit "mindfulness", an ability to identify and maintain awareness of potentially hazardous situations and to act quickly to contain or mitigate them

Organization-Fleet Experience: SSP as a High Reliability Organization

- **Findings:** Pre-launch events as well as historical factors indicate the SSP is not fully aligned as an HRO. Some examples that the SSP does not fully exhibit the characteristics of an HRO, include:
  - **Preoccupation with Success:**
    - ET foam shedding accepted as in-family event
  - **Tendency to Simplify Interpretations:**
    - Shuttle is operational and its technology is mature
  - **Insensitivity to Operations:**
    - Effect of consolidation moves on experience and skill level
  - **Non-Commitment to Resilience:**
    - Pre-disposition for post-landing vs. on-orbit damage assessment
  - **Lack of Defiance to Expertise:**
    - Limited post-launch SSC interactions with centers (OPS vs. R&D)

Organization-Fleet Experience: SSP as a High Reliability Organization

<table>
<thead>
<tr>
<th>Reason for Failure (From Board report)</th>
<th>STS-107 Pre-Launch Issues</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core &amp; Schedule Constraints</td>
<td>ORB Overrun, Mission Ops, &amp; ISS Schedule</td>
</tr>
<tr>
<td>Inefficient Risk Assessment &amp; Planning</td>
<td>Pre-Foam, Tile, &amp; RCC Fronts &amp; Potential Interactions</td>
</tr>
<tr>
<td>Understanding of Complexity &amp; (Orbittoization) Technology Maturity</td>
<td>TPS-TileRCC &amp; Foam (e.g., MGT, Install, Aiming, &amp; Repair)</td>
</tr>
<tr>
<td>Inefficient Testing (e.g., Testing, Analysis, NDE, etc.)</td>
<td>TPS-TileRCC &amp; Foam (e.g., MGT, Install, Aiming, &amp; Repair)</td>
</tr>
<tr>
<td>Poor Team Communications</td>
<td>Source: Defining of Compromised Operations &amp; Horrible Integration in Technology Areas</td>
</tr>
<tr>
<td>Inadequate Review Process</td>
<td>SFOC Transition: NASA Insight vs. Oversight</td>
</tr>
<tr>
<td>Design Errors (e.g., Inadequate specs, etc.)</td>
<td>TPS-TileRCC &amp; Foam (e.g., Aiming, Spec, &amp; Repair)</td>
</tr>
<tr>
<td>Inadequate System Engineering</td>
<td>Composite Integration Concepts (e.g., FT Foam Meting Damage)</td>
</tr>
<tr>
<td>Inadequate or Under Tolerant Staff</td>
<td>ENSG Staffing Levels, Sites, &amp; Experience* ORS-RA Inc., Aiming Works, &amp; Workload*</td>
</tr>
</tbody>
</table>

*Not a factor in STS-107

Organization-Fleet Experience: SSP as a High Reliability Organization

- **Recommendations:**
  - Re-examine treatment/ resolution of past, present & future anomalies
  - Provide for greater hands-on presence & involvement of NASA personnel in all aspects of the SSP
  - Reform pre-/post-launch reviews, add a pre-launch review, & delay on-orbit mission monitoring/support
  - Provide for improved post-launch & on-orbit vehicle assessment as well as on-orbit repair & escape
  - Establish a matrix of Subject Matter Experts to be assigned for respective technology areas impacted by anomalies

Report Volume V October 2003
Organization-Fleet Experience: Risk Acceptance in the SSP

**Background/Facts:**
- Scholars studying NASA & SSP have raised the issue of risk acceptance, overlooking/skipping to recognize the severity of possible problems (e.g., Vaughan, Feynman, etc.).

**Findings:**
- Risk acceptance may be a continuing phenomenon in the SSP.
  - Increases in waivers and “workarounds”
  - There seems to be a repeated failure to identify and attend to weak signals occurring over time.
  - “Foam loss never has been a ‘SCIF’ issue”
  - Bryan O’Connor (NASA HQ S&A Office) discusses 3 levels of the Risk Cube to describe Risk Acceptance in NASA:
    1. Known Knowns: Repeated or routine events and established facts.
    2. Known Unknowns: Known possible events, but unknown when or how they will happen. Also, recognizing the limits of one’s knowledge.
    3. Unknown Unknowns: Rare (or have yet to occur) events. There is insufficient vigilance in the process to look for their possibility.
- A possible fourth category: Unknown Knowns: Situations where an absence of data exists (known knowns), but it’s too much information to filter through & select the relevant data for a given situation in a timely manner. High signal to noise ratio (Thompson 2003). Especially relevant during crisis or unusual conditions, like mishaps.

**Recommendations:**
- MSP should increase its vigilance regarding Risk Acceptance by incorporating various preventive measures. For example:
  - A Personnel-focused Mentoring Program:
    - The MSP should establish coupling relationships between experienced and less experienced personnel.
    - Senior personnel have knowledge stores, problem resolution experience, troubleshooting, and ability to detect nuances with complex systems.
    - Such attributes allow for practicing “art” vs science of Shuttle engineering when confronted with situations where existing models and processes may not fit perfectly.
  - A Process-focused Program:
    - The MSP should consider incorporating a structured paradigm providing a disciplined approach to technical analyses & other critical processes.
      - The KNOT model (Known, Need to Know, Opinion, Thought to Be Known) is used by USAF analysts in cases of unexpected or unexplained failures. It can be used in combination with a “4th Block” model of fault-tree analysis.
### The KNOT Model

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Thought to be Error</th>
<th>Found in Error</th>
<th>Conclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure through electromagnetic interference or STS failure (as required for CPE)</td>
<td>Undesirable interaction or what is seen is not what is seen</td>
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</tr>
<tr>
<td>Failure through sensor information error (as STS failure through temperatures)</td>
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### Organization-Fleet Experience: Risk Acceptance in the SSP

- **Recommendations (continued):**
  - An Empirically-Based Program
  - The SSP should continue its development/implementation of a Probability Risk Assessment (PRA)
  - PRA is currently being developed by SSP SAMA Office; it integrates all models into a complete Shuttle PRA
  - The Shuttle Project Offices build project-specific failure logic models and perform corresponding data analyses
  - The PRA applies a linked fault tree approach to develop failure probabilities (functional, common cause, human error, & phenomenological); Bayesian updating is used when insufficient Shuttle-specific data exists to help identify Unknown Unknowns.

Taken from a training by J. Rosenmiller, 14 April 1995.
Space Shuttle Systems Integration Office

- **Action / Issue:**
  - Space Shuttle Systems Integration Office (MS) stovepiped and not organized to enhance horizontal integration of the various STS elements and projects.
- **Background / Facts:**
  - Space Shuttle Systems Integration Office (MS) supposedly conducts integration responsibilities across all STS elements and projects.
  - Tasks involving the Orbiter are worked by MV.
  - MS, MV equal on organizational charts; both at JSC.
  - Integration relationship between MS and the MSFC projects (ET, SSME, SRB, RSRM) better defined.
  - Rank for the respective managers in MS is GS-15 and MV is an SES.

Space Shuttle Systems Integration Office

- **Findings (to date):**
  - MS does not integrate the STS.
  - Office works closely with MSFC projects, MS does not integrate the Orbiter under MV.
  - MS is an integration office stovepiped to the Shuttle projects at MSFC and works with the Orbiter office.
  - If MS office properly used, could have focused away from day-to-day brush fires and worked proactively to prevent problems.
  - MS has limited integration responsibility with the SFOC (SRB) is under the SFOC contract and contracts for the ET, RSRM and SSME.
  - If all contractor elements of the STS were integrated from MS, tracking the bloodshedding might have been centrally monitored and worked.

Space Shuttle Systems Integration Office

- **Recommendations (to date):**
  - MV does not send representative to Integration Control Board (ICB) run by MS.
  - MS representation not required participant at MV Vehicle Engineering Control Board.
  - Not every bloodshedding resulted in IFA.
  - Sometimes the Orbiter office had responsibility, sometime the ET office at MSFC.
  - No contingency plan for using fault trees.
  - MV started an Orbiter fault tree.
  - MSFC started a fault tree for each of its projects (ET, SSME, SRB, RSRM) Independent of JSC.

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Organization
Maintenance

24-2  Human Factors and Maintenance Operations
24-3  Human Factors in NDE, QA, and Inspection
24-4  Human Factors in FOD Prevention
Organization-Maintenance:
Human Factors in Maintenance Error Prevention

- Action / Issue:
  - Human Factors is Critical to Error Prevention in Maintenance Operations

- Background / Facts:
  - Mistakes typically associated with the "Dirty Dozen"
  - Lack of communication, teamwork, awareness, knowledge, resources, & assertiveness
  - Absence of pressure, noise, stress, distraction, fatigue, & complacency
  - Common Management factors in MA errors lead to information dissemination, organizational policy/procedures, & supervision.
  - Common human factors in MA errors lead to communication, individual skills, technical knowledge, job/task, & AAC design.

- Findings:
  - Given projected workforce turnover, potential for QA vs QC practices to miss potential errors, recognized deficiency in oversight, and increased maintenance requirements associated with an aging aircraft.

- Recommendations:
  - Need to provide for a human factors analysis of maintenance practices and provide targeted intervention, including maintenance resource management training.
Organization - Maintenance:
Human Factors in Inspection

- Action / Issue:
  - Human Factors is Critical in NDE, GA, & Inspection Activities

- Background / Facts:
  - Primary human factors associated with inspection process effectiveness
    are training, OJT, co-worker information, understanding of fault modes, &
    expectations of faults
  - Job factors include documentation, standards, SPECS, lighting, and
    visual/physical access

- Findings:
  - Numerous inspection activities related to ET foam installation. TPS
    integrity/repair, & aging orbiter are critical to safety of flight
  - Numerous inspection activities related to orbiter and component
    construction, overhaul, and repair are critical to safety of flight

- Recommendations:
  - Conduct human factors analysis of present/future inspection procedures
    and conditions to provide for optimized Human Systems Integration
  - Observe the impact of workforce norms, complacency, etc. on the
    inspection process and provide proper oversight
Organization-Maintenance: Human Factors in FOD Prevention

- **Action / Issue:**
  - Human Factors is an Essential Component in FOD Prevention

- **Background / Facts:**
  - Human factors in FOD prevention include preventative practices, training, and personnel awareness.
  - Management factors in prevention include specialized assignments, awards programs, housekeeping guidelines, tool control, material handling, and reporting.

- **Findings:**
  - FOD concerns should not be compromised by renaming to facilitate contract award and operations; potential for FOD to create a Safety of Flight issue is great.

- **Recommendations:**
  - Provide for a human factors analysis of FOD practices, handling, and disposition to provide for optimized Human Systems Integration
  - Need to observe the impact of workforce norms, competency, etc. on the FOD prevention and provide proper oversight.
Organization
Orbit

23-4  Langley and JSC E-Mail Exchange
23-7  Engineer Simulation Training
23-8  Boeing Transition of Orbiter Support from CA to TX
Decentralization & Resilience in Handling Anomalies: LaRC-JSC Exchanges on MLG Concerns

- **Action/Issue:**
  - Decentralization is critical in detecting anomalies and providing for resilience.

- **Background/Facts:**
  - Jan 27th: JSC-LaRC engineers had phone/mail exchanges on the foam debris assessment (including charts indicating the left MLG area could be involved).
  - JSC engineers stated there was concern the MLG door was "uninsurmountable," perhaps leading to a two flat tire landing (or compromising MLG). Discussed simulating landing to evaluate outcomes, but no formal request was pending. Found doing "after hours" play-back on adnasa training underway at NASA ARC.
  - LaRC engineers expressed concerns to JSC counterparts to be prepared in case a problem arose on landing; contact management on Jan 28th on the JSC-SF concerns.
  - Reviewed previous related data run; Jan 30th provided scenarios tied to potential MLG problem (most had severe outcomes). Simulation results for a two flat tire landing provided on Jan 31st showed it was survivable/controllable.
  - Based on established working relationships, the negative scenario observations (with caveats) were passed to select JSC personnel for consideration; whereas favorable simulation results were given to a wider JSC audience for review.

- **Recommendations:**
  - Guidelines regarding communication of safety issues/concerns should be established to ensure early/complete dissemination of information to recognized government and contractor systems and technology experts who work OPB, R&D, etc. at all NASA Centers.
  - All channels of communication (e-mail, phone, etc.) should be open and encouraged to discuss/disseminate safety concerns, but assurance must be made that information is raised to appropriate management and safety oversight personnel.
  - Disseminate all information prior to decision-making sessions (if possible) for preliminary review and potential comment to increase early feedback, participation from attendees, as well as comments from interested parties unable to attend.

- **Findings:**
  - Formal dissemination of foam debris assessment did not make it directly (or in a timely manner) to all personnel involved, especially those who may have had the expertise for the proper diagnosis of associated problems and for the development of mitigation/containment procedures.
  - Ineffective dissemination leads to informal channels that can not be relied upon to get information expeditiously to affected systems/technology experts and provide an adequate chance to make inputs for decision-making.
  - E-mail/PowerPoint are tools for asynchronous communication (often to a selected audience), however they can not be relied upon to ensure understanding, influence decision-making, or elicit action (especially from non-targeted recipients/respondents).
  - Note: The actions these working level engineers took to overcome limited horizontal integration between OPB and R&D (NASA Centers) so as to network, marshal resources, and prepare for a potential contingency is an example of the resilient spirit that led to the successful return of Apollo 13.

- **References:**
  - E-mail exchanges on foam debris and LaRC-JSC interactions reporting the initial damage assessment. Complete set of email beginning Jan 23.
  - E-mail exchange on Jan 28, 2003, on assessment of potential for a breach in the landing gear door or wheel well during re-entry into Earth's atmosphere
  - E-mail exchange within LaRC regarding main gear breach concerns on Jan 31.
  - Daugherty, R. & Shultz, J. (20 MAR 03) NASA Langley Press Conference
  - NASA EOS Operations Management Bulletin 87.31
  - NASA Information Systems Directorate e-mail Guidelines
  - Pantsch, J. (23 MAR 03) Support for ISS/STS by Email: TERRA Conference
Organization-Orbit:
Engineer Simulation Training

- Action / Issue:
  - Lack of Ongoing Formal Event Simulation Training for Shuttle Engineers involved in the MMF/MER

- Background/Facts:
  - Comparisons with SSP and DoD safety performance should consider differences in training levels
  - DoD trains at all levels, across nearly all operations, with all affected personnel: An established and accepted organizational norm.

- Findings:
  - In SSP, only the Astronaut crew and Flight Control team receive ongoing formal training; the MMF conducts a simulation exercise once/18 months
  - The MER and other principle engineering support teams receive no ongoing formal training beyond initial orientation

Organization-Orbit:
Engineer Simulation Training

- Recommendations:
  - A formal training program should be developed to meet 2 major goals:
    1. Strengthen basic & advanced skills and processes during routine and unusual conditions
    2. Strengthen team integration & communication processes within & among technical & management elements, specifically the MER & MMF
  - Training should include practice problems, simulations, realistic scenario play, performance evaluation, & feedback (strengths, weaknesses, & lessons learned).
  - Seasoned engineers (i.e., mentors) should be incorporated into training exercises to continue the knowledge transfer effort (Note, particularly important to develop troubleshooting skills and situations requiring subjective judgment calls).
Organization-Orbit: Boeing Transition of Orbiter Support from CA to TX

**Action/Issue:**
- Boeing transition (1201-0303) of Shuttle operations (OPS) support function from Huntington Beach, CA (HOU) to Houston, TX (HOU) precipitated a large turnover in personnel with significant program experience and technical expertise.
- To minimize effects from a potential loss of expertise, Boeing planned a risk managed transition process, with an emphasis on key positions.
- Process was not uniformly implemented, potentially impacting support capabilities.

**Background:**
- In Detmer's March 01 testimony to the CAB, he indicated the transition was a contractor-based initiative to get "engineering closer to the customer." He indicated the full impact of the "overall cost" of the transition on the contractor was not clear.
- Pre-transition Boeing had ~1,200 jobs in HOU (984) and ~150 (12%) in HOU.
- Post-transition Boeing had ~500 jobs in HOU (28%) and ~500 jobs in HOU.
- Only 27% of Boeing incumbents transferred to HOU, requiring over 150 new positions to be filled (this included both critical SSMM and various engineering positions).

Organization-Orbit: Boeing Transition of Orbiter Support from CA to TX

**Background (con't):**
- By March 31, 2003 there were 531 total jobs that transferred from Huntington Beach to Houston and Florida.
- Of the 531 jobs that transferred, 140 people relocated from Huntington Beach. The remaining 391 positions were filled by replacements.

**Findings:**
- Boeing transition review (11/02) accomplishments listed most of replacements, completed 69% of programming training (30% completed all of the training), and replaced 89% of critical skills.
- Boeing/NOA site director indicated that further evaluation of the transition's success was under consideration to use this KCP model in their organizations.

**Recommendations:**
- Boeing performance and safety award fee scores were higher with pre-transition local SSMM.

**Findings:**
- Witness impressions of the overall transition process.
- Despite the official reports' positive tone and the site director's comments, witnesses questioned the overall success of the transition process (including knowledge capture, individual training, and exit evaluation).
- Witnesses characterized the process as compressed and, consequently, rushed.
- High-level training and communications were not provided to transition group.
- Further analysis (tests, stress, thermo, & structures) had additional concerns that the transition could impact the on-orbit report damage assessment process/findings.

Organization-Orbit: Boeing Transition of Orbiter Support from CA to TX

**Findings (continued):**
- Knowledge Capture Process (KCP)
  - Overall, the plan appeared to be both systematic and comprehensive, encompassing:
  - Knowledge capture process (KCP), to catalog incumbent expertise through questionnaires, video interviews, and feedback.
  - Critical skill checklists, based on inputs from each incumbent performing a task, containing a given "job.
  - HI competency managers and NOA Integrated Team Managers review of KCPs with corresponding checklists.
  - Risk management of the task transition process, to effectively identify, assess, and address hazards; "Risk-Flagging" areas for additional oversight based risk.
  - 15-month transition timeline that covered two shuttle missions (STS 124 and 113), providing "real-time" data.
  - 6-month period for individual job transitions, including training for new positions.
  - Certification process for key positions.
  - Established guidelines for identifying and selecting critical personnel and engineering replacement candidates.
  - Making a job candidate with respective incumbents for formal task training and monitoring whenever possible.

Organization-Orbit: Boeing Transition of Orbiter Support from CA to TX

**Findings (continued):**
- Knowledge Capture Process (KCP)
  - Video interviews:
    - The video-based interviews were intended as a "how-to" demonstration of procedures leading themselves to hands-on hardware processes.
    - Many interviewees were not asked to participate in video tours.
    - Most felt they were useful for technical, hands-on tasks, but not useful for other activities, like procedures and analysis.
    - One analyst thought this was the only useful KCP component.
  - Toolboxes:
    - Incumbents were asked to make a complete listing of all files, references, locations of guiding documents, policies, analytical tools, software, etc. that would be relevant for a particular position.
    - While this compilation was not required of some lower-level engineers, most agreed that this was the most-useful part of the KCP.
    - NOA engineers acknowledged there is continuing work being done on the toolboxes.

**Findings (continued):**
- Knowledge Capture Process (KCP)
  - Witness comments:
    - The KCP was seen as "not too bad, not too good.""Witnesses were not too useful, whereas some felt the answer KCP was not useful at all.
    - The KCP was not as specific as individual functions as a result of the interviews; interviewees were not enlightened.
    - Overall, the KCP was critically lacking in expertise across all technology areas. The content was expressed in management or informal settings, including answers, staff, and intermediate meetings.
    - NOA witnesses reported that while KCP was lacking, actual knowledge transfer process was sufficient.
  - Questioning:
    - The video questionnaires documented inputs, outputs, and products of a position.
    - Some witnesses indicated that the KCP was adequate, but could not capture decade of experience.
    - It was perceived as too brief and inadequate, as it gathered only top-level, generic information about positions.
Organization-Orbit:
Boeing Transition of Orbiter Support from CA to TX

• Findings (continued):
  Knowledge Capture Process (KCP)
  - Management Review:
    - The review of KCP products after the incident compiled them on a sparsely
      attended basis.
    - They generally indicated that their manager received 1 or in some cases
      reviewed it, and asked for clarification. In other cases they merely took it,
      with no revision or refinement.
    - The witness collectively stated there was no training on how to do the KCP,
      no standardization of the product produced, and it was not systematically
      implemented.
    - The process was more difficult for senior personnel and management team,
      e.g., to produce an effective voice discussion as stated above.
    - Overall, the KCP did not consistently follow the transition plan in many cases,
      especially for non-critical positions.

Organization-Orbit:
Boeing Transition of Orbiter Support from CA to TX

• Findings (continued):
  Selection, Training, & Certification
  - Exit criteria for the training process was unclear to instructors, other than
    completing the checklist/training plan. In some instances, the task was not
    completed or the candidate was not proficient to the task(s) by the time the
    transition ended. Some witnessed significant frustration and concern about
    this process.
  - Most OSM training and certification processes were coordinated by managers.
    They indicated the process was rigorous and completed USAR/AMS/USAA participation.
    Most OSMs held significant seniority with the SSP. Although some concerns of the
    certification process was not fully described, most people said the process
    went very well. Reports indicated that the training and certification process for
    OSMs was well documented.
  - The incumbent and candidate worked together for SSS-112 & SSS-113, two
    missions flown during the transition process. SSS-107 was the first mission flown
    after transition completion, with OSM holding primary responsibility.
  - After the transition was complete, incumbents provided further assistance only as
    requested by the new responsibilities.

Organization-Orbit:
Boeing Transition of Orbiter Support from CA to TX

• Findings (continued):
  Risk Management and Over-Site
  - SSS-107 & SSS-114 were listed as yellow due to a general replacement
    personnel generating flight products with approved work around plan and some
    system integration personnel having no certification back. The action plan to
    mitigate risk was listed as "Transition plan has been developed and tailored with
    NASA and USAF, and最后一 round until transition completed".
  - Once the transition process was complete, re-evaluation of individual risk was
    done.
  - Boeing contracted Independent Risk Assessments (IRA) for the transition.
    - The goal was to complete staff training by the end of 1200. "Victory General" is
      included: completing 90% of the training, 90% of the training, 90% of the critical
      skill training, 90% of the task list, and certified for OSM and certified
      personnel competency for all tasks.
    - The analysis indicated a 95% chance that criteria would not be met by the end
      of Dec 02. 66% chance by Nov 02, and a chance 0% chance of certification by
      date.
    - Given the situation, they recommended a "supercap" interview and pre-
      qualification process, a determination of training times, not less than, reporting dates,
      and training startup, carefully considered all training times and work on scheduling
      (especially if no "carbon copy" is leaving).
Organization-Orbit: Boeing Transition of Orbiter Support from CA to TX

Findings (continued):
Analysis from a High Reliability Organization (HRO) Perspective
- Process Audit: Boeing should have focused knowledge capture from incumbents was
  lacking, evaluation training with replacements was adequate, and training and criteria
  was inadequate to ensure it was proficient in the tasks they were to perform.
- Quality Assurance: ensuring the named candidates was proficient for both normal
  and emergency operations, operational adequacy were tested in some cases, and test
evaluations were complete and covered all limitations.
- Risk Management: assessing risk on an effort level for each transition to HSU, assess and
  prioritize training for individual replacements, examine risk after training and determine if
  risk was within acceptable range and maintain awareness of specific issues, and establish
  appropriate measures.
- Reward System: providing incentives for training replacements in a level of demonstrated
  proficiency for all jobs (not just 50Kers), and not just simply mandating the deadline to fit
  activities and get them signed off as qualified. Ensuring there are no perceived pressures;
punishments for holding off on sign-off due to deadlines.
- Command & Control: making adjustments for situations where the incumbent/contractor were
  not in command's control during the transition planning process, where the training was not fully
  completed or the incumbent was not available for the training, establishing and supporting
  monitoring relationships, and not providing for defense of networked experts to support
  emergency situations.

Recommendations
- Boeing should place additional emphasis on continued skill building and knowledge
  acquisition from seasoned incumbents to new and transitioned personnel (beyond any
  remediation).
- Boeing should develop a systematic method for incumbents and new hires/transition to
  have regular communication exchanges on both formal and informal bases (e.g.,
  VTCs, web-based bulletin boards, etc.)
- Boeing should utilize the HSU Mission Support Room for the next shuttle mission, with
  incumbent personnel "check-in" to provide oversight.
- Regular and ongoing training opportunities should be provided for new employees
  and provided by the incumbents.
- Boeing's plan for additional transitions to HCU should be reviewed to provide for
  continued knowledge capture, risk management, systematic training, and evaluation
  of proficiency. Further, the process for selecting new hires and in-house transfers
  should be reexamined for receipt critical skills, quality, and experience.
- USA should undertake costs for the complete Boeing Shuttle OPE Support transition
  skills evaluation, knowledge capture, risk management, remediation training,
  incumbent mentoring, exit criteria, and follow-on risk assessment.
**Budget and Finance Considerations**

- **Action / Issue:** Budget and Finance Considerations Influence Shuttle Program Performance
- **Background / Facts:**
  - Cost pressure may adversely influence mission success at USA and sub-contractors as ISS cost overruns take greater share of NASA budget
  - Reduction at NASA funded level would be distributed to program based on NASA priorities. Cost growth in other priority programs could negatively affect funding on the SFOG and other SSP contracts.
- **Findings:**
  - Committee reports, new media, etc. indicate extensive cost growth on ISS

**SSP Budget**

- Human Space Flight is approx 40% of NASA budget
- Space Shuttle is half of human space flight budget
- No recent large congressional cuts
- FY2001 necessary to redirect advanced areas to address cost and program management needs of the ISS

**Shuttle Budget History**

- 2002 reduced $50mil
- 2001 reduced $40mil for Mars initiative
- 2000 earmark of $40mil transfer to ISS
- 1999 reduced $31mil
- 1998 transferred $50mil to ISS
- 1997 transferred $190mil to ISS
- 1996 reduced $53mil; transferred $30mil to ISS
- 1995 general reduction $168 to Human Space Flight

**Budget and Finance Considerations**

- **Group Recommendation:**
  - NASA should accelerate move to full cost accounting of the Space Shuttle Program in order to provide the adequate future funding in NASA and Centers' budget

**Shuttle Budget History**

![Shuttle Program Budget History Graph]

- Historical Budget Request
- Final Operating Plan
- Appropriated by Congress

**SSP Budget**

![Cumulative Budget Reductions Graph]

- Millions of Dollars
- Fiscal Year
- 1995 to 2002
- 2002 cumulative budget reductions $800mil
Contract Production

26-1 Non-SFOC Contracts
26-2 Foam Application Process not Specified as Contractual Requirement
26-3 ET Not Subject to Catastrophic Loss Penalty Clause
26-4 Pressure to Decrease Costs on SRB
Contracting Issues
Non-SFOC Contracts

- Action / Issue: Non-SFOC Contracts "evolve" to shift emphasis away from cost savings
- Background / Facts:
  - MSFC has contract cognizance over Space Shuttle element contracts that are not part of the SFOC
- Findings:
  - MSFC evaluates whether contractor headcount had been reduced to minimum safe level and whether continued personnel reductions would have a negative rather than a positive effect
  - ATK Thiokol Propulsion has been Reusable Solid Rocket Booster (RSRB) supplier since 1974
  - Contracts from Buy 1 to Buy 4 included cost savings share line, allowing Thiokol to share in any savings below target cost
  - Current buy, while including a 1% incentive fee at target cost, contains no incentive for underrun

Fee Structures of Non-SFOC

- Issue: SFOC was planned to include other "element" contracts as Phase 2
- Only SRB added (1998)
- Elements not included in SFOC
  - External Tank (ET)
  - Space Shuttle Main Engine (SSME)
  - Reusable Solid Rocket Motor (RSRM)

Non-SFOC: External Tank

- Michoud Assembly Facility (GOCO) operated by Lockheed Martin
- Estimated Cost (ET Production): $2.06 B
- Estimated Fees: $134.4 M (Incentive, Employee Motivation, Award)

ET Production Award Fee

- Quality Performance 70%
  - Subcriteria: Quality of hardware; problem reporting/resolution; hardware performance; safety performance
- Management Performance 30%
  - Subcriteria: Project management; flight support; contract management
Non-SFOC: Space Shuttle Main Engine

- Contractor: Boeing (formerly Rockwell/Rocketdyne)
- Current Contract Thru December 2003
- Estimated Total Cost: $1.04 B
- Estimated Fees: $123.6M (fixed, incentive, award)
  - 12% of cost

SSME Award Fee

- Management performance: 30%
- Flight support: 40%
- Safety, Reliability, QA: 30%
- Current Rating:
  - June 2002: 81.2
  - December 2002: 91.4

SSME Award Fee History
Contracting Issues
External Tank

- Action / Issue: Foam Application Process not specified as contractual requirement
- Background / Facts:
  - External Tank Contract NAS8-00016 does not specify the application process to be used by Lockheed Martin Michoud Assembly Facility for the External Tank
  - ET Statement of Work (SOW) as included in the contract imposes the ET End Item Specification, CM82 and materials Process Control Plan as Type I documents.
  - Items below SE 16 level include engineering drawings, product processes and manufacturing plan (MPP)
  - NASA and DCMA are to review any changes to the contractor that affect form, fit or function

Contracting Issues
External Tank

- Group Recommendation:
  - NASA MBPC should consider specifying the ET Foam application process in the contract End Item Specification to maintain consistent control of the process

Contractual Flow Down for TPS Requirements

External Tank Contracts

Statement Of Work From Contracts

Identification of Controlling Type I Documents

NAS8-36200
(5th Bay)
ET-61 thru ET-125

NAS8-00016
(6th Bay)
ET-122 thru ET-156

ET End Item Specification

Material & Process Control Plan

Identifies all Technical Requirements for the ET

Implements all Type I Requirements Documents for TPS

Statement of Work

(Section 1.1 of Contract)

Contracting Issues
External Tank

ET Prime Document

CM82# ET End Item Specification

CM82 identifies all the technical requirements that pertain to the ET. This document includes a cross reference between the NAS8-97700 Volume X specifications and the applicable ET paragraphs.

ET Independent Document

SFEs

SFEs identify the materials and processes for building the ET.

NAS8-36200
5th Bay
ET-61 thru 125

NAS8-00016
6th Bay
ET-122 thru 156

5th Bay
ET-61 thru 125

6th Bay
ET-122 thru 156

Statement of Work

(Section 1.1 of Contract)
Contracting Issues
External Tank

- Action / Issue: External Tank used on STS-107 not subject to Catastrophic Loss Penalty Clause
- Background / Facts:
  - External Tank 93 was delivered in 2000 under MSFC contract. Tank was held by the Government until needed
- Findings:
  - Current buy for Tanks ET-122 through ET-156 contains a catastrophic loss penalty clause
  - Category I Failure, death of crew or loss of orbiter: $10M
  - Category 2 Failure, mission failure: $3M
  - Contract NAS 6-00016 was awarded September, 1999 for production of 35 tanks

Contracting Issues
External Tank

- Findings (con’t):
  - In negotiation, Lockheed Martin wanted fee raised considerably before accepting a catastrophic loss penalty
  - MSFC decided benefit of including the clause did not support the cost of the additional
- Group Recommendation:
  - Should NASA determine ET contractor culpability, complete contract review should be accomplished to identify whether other provisions exist in prior contracts to assign penalties or fee forfeitures

RSRM Loss Provisions

- Fee reduction for loss of crew, vehicle or mission
- Category I failure
  - Incident directly attributable to an RSRM
  - Results in loss of life or vehicle
  - Forfeiture of $10M plus all fee earned or available during award fee period in which loss occurs
- Category II failure
  - Incident directly attributable to an RSRM
  - Results in loss of mission
  - Forfeiture of $5M plus all fee earned or available during award fee period in which loss occurs

SSME Loss Provisions

- Fee reduction for loss of crew, vehicle or mission
  - Category I failure
  - Incident directly attributable to an SSME
  - Results in loss of life or vehicle
  - Forfeiture of $10M plus all fee earned or available during award fee period in which loss occurs
  - Category II failure
  - Incident directly attributable to an SSME
  - Results in loss of mission
  - Forfeiture of $5M
  - Category I and II failures to be determined by a failure investigation board per NPR 3021.1
  - If failure determined to be both category I and II, only category I penalties shall be applied
SRB Under SFOC

- **Action / Issue:** Increased pressure to decrease costs on the Solid Rocket Booster (SRB) portion of SFOC may have detrimental effects on SRB technical issues.

- **Background / Facts:**
  - SRB was not originally part of the SFOC, but was added in 1998. It is currently the sole Space Shuttle hardware element included in the SFOC. The External Tank, Space Shuttle Main Engine, and Reusable Solid Rocket Motor are each covered by separate contracts with their own incentive plans.

- **Findings:**
  - SRB is weighted at 10% of SFOC Award Fee rating.
  - USB achieved significant cost savings under the predecessor SRB contract, declaring an underrun of $46 Million though 1999.

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SRB Under SFOC

- **Group Recommendation:**
  - Savings are implemented by the reduction in manpower, but without specific identification about which (unnecessary) tasks were eliminated or efficiencies achieved.

  - **Group Recommendation:**
    - JSC should examine whether some elements should be excluded from contract cost savings incentives.
Contract Maintenance

27-1 SFOC Fees and Cost Limitations
27-2 TMR Weights
27-3 USA Benefits
Space Shuttle Operations Contract

- Action / Issus: SFAC award fees, incentive fees, performance fees, and cost limitations may affect the profitability of the contract
- Background / Facts:
  - SFAC is susceptible to funding limitations
  - Reduction at NASA funded level would be distributed to program based on NASA priorities. Cost growth in other priority programs could negatively affect funding on the SFAC and other SSP contracts.
  - Using commercial business practices can reduce cost and provide increases in profit incentives for cost reduction and performance
- Findings:
  - Fee Structure (see following slides)
- Group Recommendations:
  - NASA should review contract history to evaluate whether fee plan is rewarding cost savings at expense of performance

SFOC Performance Fee Plan

Performance Fee Incentive Criteria

- Earned Performance Fee

- Performance Penalties

SFOC Performance Fees

- Available fee: $6 million (STS 80 - STS 91), $6.8 million (STS 95 STS 110)
- Total earned over 31 flights: $190 million
- Fees forfeited:
  - $1M STS 80 (OV-102), January 1997 (challenged by USA, resolved September 1997)
  - In Flight anomaly (IFG), inability to accomplish major mission objectives
  - $1M STS 92 (OV-103) September, 2000
  - 24-hour launch delay

SFOC Performance Fees (cont)

- Missed manifest launch date by more than 7 days - due to workmanship damage to wiring
- $2.87M STS 99 (OV-105), March 2000
- Workmanship damage to wiring
- $2.87M STS 101 (OV-104), June 2000
- Workmanship damage to wiring
- $1.435M STS 109 (OV-102), May 2002
- Missed manifest date, ready for launch criteria not met
**Award Fee**

- Six-month periods
- Scores range from 0-100, reflect per cent of available fee
- Fee Determining Official (FDO) signs the performance determination
- Safety Score and Performance Score
- Contracting Officer's Technical Representative (COTR) recommends based on input from Performance Evaluation Board

**Award Fee History**

- Performance Evaluation Team (PET) rates USA on 13 functional areas.
- Technical Management Representatives (TMR) provide numerical evaluations on areas of emphasis
- Identify Strengths and Weaknesses

**SFOC Award Fee**

- Earned
- Available

**SFOC TMR Ratings**

- Budget Per Cent
  - Full Scale Launch and Landing
  - SFP Eng
  - MOD
  - Logistics
  - SRB
  - Sys Int
  - Avionics/Software
  - D Station Ops
  - SSP Business
  - D SSP P&MA

**Boeing Subcontract to SFOC**

- Boeing subcontract makes up largest share of SFOC
- Subcontract value is $2.3 B
  - Cost of $2.1 B
  - Fees total $197.4 M
- Award fee plan mirrors SFOC
- Award fees scores track to within 5% of SFOC score by agreement
Contracting Issues

**SFOC**

- **Action / Issue:** Technical Management Representatives score weightings may hide substandard performance on contract requirements.
- **Background / Facts:**
  - Each Technical Management Representative (TMR) assigns USA a performance grade in each of 6 areas. TMR Scores are weighted based on an individual share of the budget.
  - Weighted scores are totaled to provide recommended score.
- **Findings:**
  - 13 TMRs rate contractor performance every 6 months.
  - Weighted scores become the recommendation to the PEB.
  - Weights of TMRs on small share elements "disappear" when summary number produced.

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**SFOC TMR Weighted Ratings**

- **Group Recommendation:**
  - NASA should review low ratings regardless of budget weights; consider assigning award fee pools to each TMR to reward performance in each area rather than aggregate.

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**TMR Weighted scoring**

- KSC Launch and landing: 27.96%
- SSP vehicle engineering: 17.67%
- MOD: 14.47%
- Integrated Logistics: 12.03%
- Solid Rocket Booster: 9.26%
- SSP SYS INT: 5.99%
- Avionics and Software: 5.48%
- Station Ops and Util: 2.69%
- SP Business: 0.60%
- SSP S&MA: 1.09%
- Management Int: 0.39%
- FOOO: 0.27%

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**SFOC TMR Weighted Ratings**

- KSC Launch and Landing weighted at 30%
- Vehicle Engineering weighted at 17%
- System Integration weighted at 6.5%
- Safety and Mission Assurance weighted at 1.1%
- Reinforces commitment to meeting manifest.
USA Employee Benefits

- Action / Issue:
  Potential "Substandard" United Space Alliance (USA) Benefits package May Impact Workforce Retention, Quality, and Morale

- Background / Facts:
  - USA's employee benefit package is viewed by some as being below aerospace industry average.
  - Defense Contract Audit Agency (DCAA) conducted audits of several areas of compensation including:
    - Compensation System Internal Controls
    - Fringe Benefits
    - Health Care Cost

USA Benefits

- Compared to Chamber of Commerce Study of companies with over 5,000 employees, USA is excessively generous
- Industry-wide healthcare company contribution 83%; employee contribution 17%
- Watson Wyatt survey of comparable companies: company contribution 83%; employee contribution 14%
- USA pays 92% of employee healthcare costs
- Also, excessive Paid Time Off (PTO) not charged as leave
- At least one more paid Holiday than average
- DCMA suggested that USA could save $12 million annually by REDUCING benefits to comparable average

- Federal Acquisition Regulations (FAR) directs that compensation be considered sum of ALL pay and benefits, rather than Pay Off Benefits separately

- Group Recommendation:
  - Perception of poor benefits may be in comparison with heritage aircraft industries (Lockheed, Boeing) where large hourly labor force historically drives generous benefits packages. There is no support to the suspected issue and it should be disposed of.